BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B71 02018

SUBJECT: Status of Nuclear Flight System Definition Studies - Case 237

DATE: February 9, 1971

FROM: D. J. Osias

ABSTRACT

Three contractors, Lockheed, McDonnell Douglas, and North American are conducting parallel Nuclear Flight System Definition studies, which, including the present follow-on contracts, will run to May, 1971. The objective is to provide the conceptual design, mission analysis, and development requirements for a nuclear propulsion system, with emphasis on cislunar shuttle applications. This memorandum summarizes the contractors' work and comments on the emphasis of their studies.

Each contractor sized the nuclear shuttle for an earth orbit to lunar orbit payload of 119,000 lbs with return of the shuttle to earth orbit, as in the NASA Integrated Plan. The resulting stages have propellant capacities of about 300,000 lbs of LH_2 and propellant mass fractions of 0.75 to 0.80.

Two basic configurations have evolved from the studies: the standard design with a single large propellant tank (33 ft diameter); and a modular design assembled in space from several small tanks, each of which can be carried in the Space Shuttle.

The cost to develop the nuclear stage is estimated to be around $1 billion, including a flight test but not including NERVA engine development costs. Production of the nuclear vehicles is estimated to cost around $60 million each, including the engine at $13 million.

The author's principal comments on the contractors' work and the direction of the studies are as follows:

The studies are providing an excellent base for more extensive studies and for decisions regarding nuclear propulsion.

Some of the planned orbital operations may be more difficult or less practical than is suggested by the contractors, primarily because of the nuclear radiation environment. However, it is recognized that radiation fields, shield weights, and remote manipulation are not well understood at this point.

The operational complexity of assembling a modular nuclear shuttle in space may be a serious drawback, despite detailed descriptions that have "demonstrated" the assembly procedure.

Further definition of manufacturing, facilities modifications, and testing could receive less emphasis until some of the operational aspects of the nuclear shuttle are better understood.

BELLCOMM, INC.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B71 02018

SUBJECT: Status of Nuclear Flight System Definition Studies - Case 237

DATE: February 9, 1971

FROM: D. J. Osias

MEMORANDUM FOR FILE

I. INTRODUCTION

The Nuclear Flight Systems Definition Study (NFSD) began in July 1969 as three parallel, 10-month studies of expendable nuclear stages for both manned and unmanned missions. The objective of the study was "to provide detailed analysis, conceptual design, and development requirements of a nuclear propulsion system, including its evolution from a flight test stage to an operational injection stage." The contractors were Lockheed Missile and Space Company (LMSC), McDonnell Douglas Astronautics Company (MDAC), and North American Rockwell (NAR). The impetus for beginning this study was the decision to move toward development of the NERVA (Nuclear Engine for Rocket Vehicle Application) engine to flight readiness by late 1977, and the attendant requirement for a stage to use as a test vehicle. Although not clear from the title, the NFSD study is concerned with the nuclear stage and its interfaces with the engine, but not with the NERVA engine itself.

Around the start of the study, the "Integrated Plan for Space Utilization and Exploration for the Decade 1970-1980," was published by NASA.[1] In the Integrated Plan, which was accepted as a description of NASA goals, the primary application for nuclear propulsion is a Reusable Nuclear Shuttle (RNS)* to carry men and supplies between low earth orbit and either lunar orbit or geosynchronous orbit. In response to the NASA planning, the NFSD study was redirected so that primary emphasis would be given to cislunar shuttle applications (reusable) of the nuclear stage and secondary emphasis to planetary missions. Schedule-wise, this occurred immediately after the first interim briefing in October, 1969. RNS size and configuration were to be derived by the contractors in accordance with the payload requirement in the Integrated Plan. The NERVA I engine (75,000 lbs thrust) was to be used for propulsion. In January a traffic model and flight schedule was provided by the Marshall Space Flight Center, the contracting agency. Otherwise the contractors were free to design the stage in accordance with their own recommended operations and missions.

---

*RNS is sometimes interpreted as reusable nuclear stage but the difference is immaterial.

The work prior to the October redirection has been denoted as Phase I,[2-4] and that from October to May 1970 as Phase II.[5-13] Follow-on or Phase III studies by the same three contractors are continuing for another 12 months, ending in May, 1971, and will complete the preliminary design, or Phase A work[14-19] as it is called by NASA project planning. The Phase III study is titled Nuclear Shuttle System Definition Study.

The objectives and direction of Phase III are the same as those of Phase II, except that mission operations are given more attention. Also, all contractors are required by MSFC to consider only stages with a propellant capacity of 300,000 lbs. Chronologically, mission operations have been studied heavily during the first portion of Phase III, with some attention to performance and engineering trade studies.

This memorandum presents a brief summary of the work completed by the NFSD contractors as given in the formal review presentations and in final reports. The discussion includes the author's comments and recommendations, particularly with regard to areas requiring further study, and draws conclusions based on the information presented. The direction and some preliminary findings of the current Phase III studies are also discussed. Although not part of the NFSD study, a description of the NERVA engine and its performance and technology is presented.

Before discussing the details of RNS performance and construction, a brief introduction to nuclear propulsion and its applications is in order. A nuclear rocket basically consists of a nuclear reactor through which propellant is passed. The heat from the reactor, created by nuclear fission, takes the place of combustion in conventional rockets. As in chemical rockets, the propellant is fed to the reactor by a turbopump and the heated gases are expanded through a nozzle producing thrust; but there is no combustion, so only a single fluid is necessary. The only propellant presently being considered seriously is hydrogen because of its low molecular weight, which produces almost twice the specific impulse (Isp) of the best chemical rockets. There are, however, moderate propellant storage problems resulting from the low boiling temperature, and the low density of liquid hydrogen which makes storage tanks large. Another disadvantage of the nuclear rocket engine, regardless of the propellant, is its relatively high weight for the thrust produced. The NERVA engine now being developed is expected to weigh about 23,000 lbs and produce 75,000 lbs of thrust, for a thrust to weight ratio of 3. By comparison, the hydrogen/oxygen engine for the Saturn V has a thrust to weight ratio of 70. For manned missions, additional radiation shielding weight will probably be necessary. However, the high Isp achieved through low molecular weight outweighs these disadvantages in some applications.

The NERVA engine development is currently planned for a flight readiness date of 1978 or 1979.

II. PERFORMANCE

Payload capabilities of the RNS were calculated by the NFSD contractors for 4 missions: lunar shuttle, geosynchronous shuttle, manned planetary, and unmanned planetary and deep space probes. The unmanned missions were evaluated for both reusable and expendable modes. Vehicle sizes and mass fractions were derived by the contractors as discussed below.

A. Cislunar Missions

The study guidelines issued in October 1969 specify that the RNS is to be sized for the payload requirement of 119,000 lbs to lunar orbit with empty return of the RNS to low earth orbit. This is the payload capability of the nuclear shuttle in the NASA Integrated Plan. However all three contractors sized the RNS with considerable margin to allow for plane changes and/or rapid return. The resulting stages have propellant capacities of around 300,000 pounds, and mass fractions of 0.75 to 0.80. With 30° plane changes on both outbound and inbound legs, the 300,000 lbs of propellant is appropriate for the nominal 119,000 pound outbound payload with empty return of the shuttle to earth orbit. Orbit to orbit transfer time is 77 hours. The payload for a mission with <u>no</u> plane changes and 77 hour transfer times is around 160,000 lbs to lunar orbit with empty return.

Figure 1 shows the performance data calculated by the contractors and used to size their vehicles. Lunar shuttle payloads are given as a function of propellant capacity of the RNS. The spread in the values is due primarily to the different estimates of RNS inert weight (as derived in the course of the studies), but it is also influenced by assumptions of parking orbits and the attendant velocity requirements. The conclusion to be drawn from the data is that an RNS with a 300,000 lb LH_2 capacity can deliver between 120,000 and 160,000 lbs to lunar orbit and return itself empty to low earth orbit. However, according to NAR's data if payloads of 120,000 lbs are delivered using only low velocity trajectories, the propellant capacity of the RNS can be reduced to around 260,000 lb. MDAC's data indicates a possible reduction to around 295,000 lb from 335,000 lb of LH_2 (their baseline).

One reason for selecting a larger-than-necessary stage is the superior performance (payload per pound of propellant) of larger stages over that of smaller stages because of the increase in RNS propellant mass fractions with size. Also, the larger stages reduce the constraints on operational schedules. The weight statements for all baseline vehicles are shown in Tables 1-4.

The RNS payload capability to geosynchronous orbit is about the same as to lunar orbit, although it varies considerably with orbital inclination. Since there is no need to carry propellant for a landing stage, such a large capability is probably not necessary except for delivering one or a few space stations.

B. Planetary Missions

The performance of the RNS as an injection stage for unmanned missions is shown in Figure 2, from NAR. Payload is shown for both reusable and expendable modes, and also for a reusable RNS with an expendable, chemical, kick stage to substantially increase the velocity capability. It can be seen from the figure that without a kick stage, a significant payload penalty is paid for reuse. An RNS in the reusable mode can provide only about 15,000 fps of ΔV (one-way), which is sufficient for a Mars surface sample return but not for Grand Tour missions. In the expendable mode, the velocity potential is over 30,000 fps.

For manned Mars missions, NAR assumed a payload of 280,000 lbs at earth departure of which 130,000 lbs was left in elliptical orbit at Mars and 150,000 lbs was returned to earth orbit. Highly elliptical earth orbits (24 hour period) were assumed for both departure and return. NAR found that such a mission with recovery of all RNS's would require at least 2.3 million pounds of hardware and propellant to be placed in a 24 hour earth orbit. This requirement is equivalent to a considerably larger weight in low earth orbit. Neither the weight in low earth orbit nor the weight for a chemically propelled mission were reported.

Lockheed reported a propellant requirement of only 1.5 million pounds in low earth orbit for the 1986 opposition class Mars mission. One reason for the lower weight appears to be that only one third of the tankage weight that departs from the 24 hour elliptical orbit is returned to earth. The NAR and Lockheed payloads are about equivalent.

C. Commentary

The traffic model specified in the guidelines for the Phase II and early Phase III NFSD studies requires about 15 nuclear shuttles over a 10 year period, each making 10 trips carrying 100,000 lbs to the moon. This represents a rather sizable program of lunar exploration, which may not be realistic. A lesser program would increase the overall cost per pound of lunar payload and might also affect the sizing of the RNS and the comparison between chemical and nuclear shuttles. (Such a comparison, including the effects of payload requirements, is presented in Reference 20.) During Phase III the study guidelines were modified to include traffic models of 2, 4, 6, 8, and 10 flights per year. Although it is recognized that the availability of a large RNS would encourage a more extensive lunar program and would reduce the cost and effort required for launching a manned planetary program, it is felt by this author that an attempt to emphasize an overly ambitious program could destroy interest in a cislunar program. The study of reduced traffic models is a worthwhile addition to the study. The effect of the less frequent flights has not yet been reported.

III. STAGE CONSTRUCTION

A. Configurations

Until the "Integrated Plan" was published in July, 1969 nuclear stages were envisioned as expendable vehicles for use primarily on manned Mars missions. The propellant tanks were 33 feet in diameter, sized to carry propellant necessary for between 10 minutes (with the larger Nerva II engine*) and 1 hour of operation. This design with a large single tank was carried over to the RNS application, but with the concept of the Space Shuttle

---

*Nerva II was a 200,000 to 250,000 lb thrust engine that is no longer being considered. The present Nerva engine was previously called Nerva I (75,000 lbs thrust).

as the basic earth-to-earth-orbit transportation and the phasing out of the Saturn V, the idea of assembling a nuclear rocket in orbit from several small modules also became attractive (see Figure 3). In this concept, tank modules and the other parts of the nuclear stage would be sized to be carried to orbit inside the cargo bay of the Space Shuttle. Several trips would be necessary to assemble the modular, or multiple tank, RNS in space, but the need for a large-lift launch vehicle would be eliminated.

The NFSD study has examined both the single tank and the multiple tank RNS's. The single large tank configuration has lower structural weight (in most analyses) and is operationally simpler, but it requires a large-lift launch vehicle to place it in earth orbit. (Even with the INT-21 it could not be launched fully loaded.) The modular vehicle has lower launch costs because it is compatible with the Space Shuttle. Additionally, the several small tanks permit each tank to be vented to space when its propellant is exhausted (which reduces the weight of the residual gas during subsequent burns), may require less radiation shield weight, and may permit reduced meteoroid shielding because of inherent redundancy.

North American Rockwell is emphasizing the single tank vehicle in their study, Lockheed is emphasizing the multiple tank concept, and McDonnell Douglas is dividing their effort about equally between single tank and modular versions of the RNS. This division of effort was specified by MSFC. MDAC denotes the single and multiple tank concepts as Class 1 and Class 3, respectively, and that notation will be used here. (Class 2 was a configuration composed of two intermediate size tanks, 22 feet in diameter, arranged in tandem, but it was abandoned after the interim briefing in January, 1970.) Several different configurations have been studied for both Class 1 and Class 3 vehicles.

A.1 Single Tank RNS

Variations in the Class 1 configurations include choices between load carrying tank and load carrying external shell, elliptical and conical aft bulkheads, internal cell construction and single propellant volume, and hybrid and standard designs (see Figure 4). The hybrid design has a small propellant tank between the engine and the main tank, which decreases the effective cone angle, maintains propellant in a favorable location for radiation shielding, and simplifies pressurization. The standard design is the normal, one tank configuration. The hybrid design was presented only by MDAC until the middle of Phase III, when NAR also considered it. The other configuration alternatives were studied by all three contractors. However, many of the selections were made early in the study and some of them were dropped from consideration in the course of the work. This is especially true for LMSC, which devoted little effort to the single tank RNS after the first few months of the study.

All three contractors selected the integral tank design (load carrying tank) because of its lower launch weight and reduced production and development costs. With the alternative load carrying shell design, the external shell would sustain the aerodynamic loads during launch and be jettisoned prior to RNS operation, resulting in lower operational weight for the RNS. However, this lower weight was judged to be less important than the lower cost and lower technological risk of the integral tank.

The early designs for nuclear stages (prior to 1968) showed elliptically shaped aft bulkheads. When nuclear radiation at the crew compartment was found to be a major problem, some effort was devoted to redesigning the stage in order to minimize shielding weight while reducing the radiation doses to acceptable levels. At first a conically shaped tank bottom with a 15° half-angle cone was found to give a good balance between structural weight and radiation shield weight that would reduce the crew radiation dose substantially. In more recent designs, the recommended half-angle of the conical bottom is 7.5 to 10° instead of 15°. Although not a problem, propellant heating by radiation is also reduced.

Another structural modification, the internal cell, can also be used to reduce the radiation dose. The internal cell, or standpipe, remains full until the surrounding tank is drained (see Figure 4). Hence, propellant is maintained in a narrow column between the engine and the crew and provides maximum radiation shielding when only little propellant remains.

During Phase II, each of the contractors selected what he considered to be an optimum configuration. MDAC recommended the hybrid construction, consisting of a 100 inch diameter tank between the engine and the main propellant tank, which is 33 feet in diameter (see Figure 4). The large tank has a 10° half-angle conical bottom with no internal cell, and the small tank fits inside the 10° cone described by the large tank. NAR selected an elliptical tank botton and a 60 inch radius internal cell. At that time they felt that with the standpipe, the additional benefit derived from the conical tank bottom did not justify the extra weight of the tank and interstage structure. The standpipe adds about 2300 lbs. During the most recent portion of Phase III, NAR has switched to an 8° conical tank with a 25" end radius and no internal cell. LMSC adopted a 15° half-angle conical tank bottom for their single tank RNS. However, they devoted relatively little effort to the Class 1 RNS, but rather concentrated their efforts on the Class 3 vehicles.

Although no two contractors selected the same configuration, all three recommended a modification to the original nuclear flight system that would reduce the radiation shield weight. One reason for the three different optimum configurations is that radiation calculations are not accurate, and hence the tradeoffs between structural modifications and shield weight are not well understood. Estimates of the weight, cost, and operational complexity of each configuration are not exact either.

A.2 Modular RNS

A number of configurations are also possible with the Class 3 vehicle. Tank size and shape are dictated by the dimensions of the space shuttle cargo bay, so most of the variety is in the arrangement of the tanks. However, since the space shuttle design has not yet been firmly established, the contractors have also considered a few options in addition to those that would be compatible with a 15 ft by 60 ft compartment. Figure 5 shows several candidate configurations noted by MDAC. The propulsion module, which consists of the engine and a small propellant tank, is identical to the small propellant tank and engine in the Class 1 hybrid configuration. MDAC selected the planar configuration for use with 15 ft diameter tanks and the tandem arrangement for 22 ft diameter tanks. The selection was based primarily on radiation levels, with anticipated flight control problems precluding use of a 15 ft diameter tandem configuration.

Lockheed recommends a configuration similar to that in Figure 5 labeled "Cluster (central void)", except that they use 7 tanks instead of 8 as shown. The tanks are attached to a structure called a space frame, which also serves as a mount for the vehicle subsystems, such as the electrical power supply, astrionics, communications, and propellant management systems, that are located in the central void region. The space frame can also be extended radially outward beyond the tanks to support thermal insulation, meteoroid shielding, and the reaction control system. This concept is illustrated in Figure 6, which shows uninsulated tank modules inside a sheath of insulation and meteoroid shielding that surrounds the entire ring of 6 tanks. Normally each tank is insulated individually.

A.3 Weight Summaries

The stage inert weights and subsystem weights calculated by the three contractors at the end of Phase II for each of several configurations are given in Tables 1 through 4. Some items, however, are missing from some tables, such as propellant reserves and residuals and radiation shield weights. Propellant mass fractions (also not included by the contractors in most of the weight summaries) vary from 0.75 to 0.80.

A.4 Launch Vehicles

The Class 3 versions of the RNS are designed specifically for launch by the Space Shuttle, whereas the Class 1 vehicles are intended to be launched by the first two stages of the Saturn V. However, with Saturn V production halted, alternative launch vehicles must be considered for the Class 1 RNS. Three methods for operation without the Saturn V have been identified: First, the RNS could be launched by a Space Shuttle booster with an SIVB (or other chemical stage) as the upper stage. Second, the NERVA engine could be replaced by a chemical engine and an oxygen tank, permitting the RNS to be used as the second stage of the Space Shuttle. Third, the NERVA engine could be started sub-orbitally, flying itself to orbit with nuclear propulsion, although, this probably would not be allowable for reasons of safety. Launch of Class 3 vehicles would be simpler, but the advantages could be negated by the complex operations required to assemble the stage in orbit.

B. Subsystems

B.1 Meteoroid Shielding and Thermal Insulation

All contractors structurally combine high performance thermal insulation with the meteoroid shielding. That is, layers of foam and multilayer insulation are placed either between the meteoroid bumper and the tank wall or between the two bumper layers of a double bumper meteoroid shield. Although design details vary among the contractors, each incorporates an aluminized mylar, multilayer insulation.

The contractors were required to use the meteoroid flux and penetration models contained in "Space Environment Criteria Guidelines for Use in Space Vehicle Development (1968 Revision)," NASA TMX-53798, October 31, 1968. Both NAR and Lockheed allowed cratering of the tank wall by meteoroid debris, except in the most recent portion of the study when Lockheed allowed no tank damage. For Class 1 systems, Lockheed estimates 6,500 lbs for meteoroid shielding for 0.995 probability of no meteoroid punctures in 1 year. MDAC estimates 8,500 lbs and NAR 12,000 lbs for meteoroid shielding and insulation giving the same protection. By contrast, an estimate based on a Bellcomm study[21] gives the weight of a meteoroid shield without insulation for a similar stage as over 10,000 lbs, and probably greater than 15,000 lbs. The Bellcomm study used the meteoroid environment specified in Reference 22, which is essentially the same as that used by the contractors, but no cratering of the tank wall was allowed. The Bellcomm study is also careful to point out that accurate calculations of shield requirements are impossible at this time due to uncertainties in the meteoroid environment and in the quantitative effects of bumpers on actual meteoroids.

For the Class 3 vehicle meteoroid shields, analyses by Lockheed and North American Rockwell show the modular RNS to require almost the same weight of meteoroid plus insulation weight as the corresponding Class 1 designs (6,500 and 12,000 lbs), which is apparently due to increased insulation and decreased meteoroid shielding. McDonnell Douglas, however, showed the Class 3 RNS in the Phase II analysis to require 14,000 to 15,000 pounds of thermal insulation plus meteoroid protection, compared to 8,500 pounds for the Class 1 RNS, but their latest Phase III results for the modular vehicle show less than 9,000 lbs.

As mentioned in connection with the space frame, Lockheed suggests the possibility of mounting the meteoroid and thermal protection for the Class 3 RNS outside the assembly of tanks, instead of insulating and shielding each tank individually.

All of the contractors show that the high performance insulation provides satisfactory thermal control for planetary missions, but it is not clear that the analyses were made in detail. That is, heat leaks through tank supports, plumbing, and conduits do not seem to be completely accounted for.

B.2 Reaction Control System

In the Phase II final briefing, NAR presented a fairly complete description of the reaction control system (RCS) for the Class 1 vehicle. They specify twenty 1,000 pound thrusters arranged in four groups of five each and placed at 90° intervals around the forward skirt of the RNS. The 1,000 pound thrust level is sized for a translunar midcourse correction of up to 100 ft/sec. If the midcourse correction can be accomplished with the NERVA engine, the RCS thrusters can be reduced to 500 pounds thrust and still provide the required pitch and yaw acceleration of $0.5°/sec^2$ in lunar orbit with maximum payload.

NAR selected a gaseous O_2/H_2 propellant system for the RCS. They considered gaseous hydrogen bled from the NERVA engine but anticipated problems with hot gas storage, tapoff of high temperature hydrogen, and interfaces with the RNS. Hypergolic systems based on monomethylhydrazine (MMH) and nitrogen tetroxide (N_2O_4) were also considered but were rejected because of operational complexity associated with orbital delivery of propellant and maintenance services because of long term incompatibility of materials.

Lockheed and McDonnell Douglas did not present any analysis of RCS requirements or candidate systems in their Phase II final briefing, but did treat the subject in the final reports. MDAC concluded that thrusters of 10 to 100 lb thrust are sufficient unless the RNS is required to provide its own docking propulsion, in which case 500 pound thrusters would be necessary. Like NAR, they selected a cryogenic system.

Lockheed recommended an earth-storable system (MMH and N_2O_2) unless total mission impulse requirements exceed 600,000 lb-sec, in which case a hydrogen/oxygen system might be preferred. They list the thrust level as 100 lbs, the total thruster weight as 400 lbs, and the RCS propellant for a baseline mission as 1200 lbs.

B.3 Pressurization System

Startup of the NERVA engine is dependent upon using the pressure in the propellant tank to begin operation. As the first flow of hydrogen is heated in the nuclear reactor, it drives the turbopump, which in turn feeds more hydrogen to the reactor. As the flow and turbopump speed increase, some hydrogen gas is fed back to the propellant tank to reach and maintain the proper pressure, which is near 25 psia, but varies among the designs.

Because the hydrogen propellant is in a saturated condition during storage, with no prepressurization the propellant supplied to the engine during startup is a liquid-gas mixture. Recent changes in the engine requirements now permit a liquid-vapor mixture at low powers, thereby eliminating the need for the prepressurization system.

These changes were instituted by Aerojet because the stage contractors found that only slight modifications to the NERVA specifications were necessary to eliminate the need for the prepressurization system. Hence the overall stage weight and complexity were minimized by allowing more vapor into the pump at low power levels. At higher power, pure liquid is still required, and this is guaranteed by increasing the tank pressure as the engine power increases.

B.4 Astrionics

The astrionics system comprises electrical power, guidance and navigation, communications, and data processing. Reported weight estimates are not always consistent, even for a single contractor. Values ranging from 1,500 lbs up to 8,000 lbs are found, but it is not clear that all estimates include the same items. In Phase II, for example, Lockheed's weight breakdown showed about 1,500 lbs for navigation, guidance, data management, communications, and electrical power, but elsewhere the instrument unit weight was given as 4,166 lbs. NAR listed the astrionics weights as 8,000 lbs, and MDAC's estimate was 3,400 lbs. Phase III values vary from 1,850 (with solar cells) to 6,000 lbs. A compromise of the various weight estimates might be 3,000 to 4,000 lbs.

B.4.a Guidance and Navigation

The guidance and navigation system is to be suitable for both manned or unmanned missions. The MDAC Phase II final report[12] describes the requirements of the system and finds none that cannot be met. They recommend an autonomous system; that is, one that can function without communication with either Earth or a space station. The other contractors reached similar conclusions.

B.4.b Electrical Power Supply

North American and McDonnell Douglas selected fuel cells as the primary power source with secondary power for peak loads supplied by batteries, assuming that resupply between missions represents no great cost or inconvenience. In contrast, Lockheed showed solar cells with rechargeable batteries to be lightest and least costly for lunar ferry missions. The discrepancy is not explained, nor does it appear that consideration was given to the deployment of the solar cells, which must be retracted during engine operation (when power needs are high) to avoid secondary radiation to the crew, possible radiation damage to the solar cells, and thrust loads.

MDAC estimated the peak electrical power requirements to be between 3.7 and 7.4 KW, with a total mission power requirement of between 175 KW-hr and 1,200 KW-hr. The weight estimates for fuel cell systems to meet these minimum and maximum power requirements, with resupply after each mission, are 740 and 2,030 lbs, respectively, including consumables for one mission. NAR estimates the total power to be 9.2 KW-hr per mission, with a peak power of 4.6 KW.

B.4.c Communications and Data Management

The communications and data systems were described by the contractors in general terms. Detailed requirements cannot be accurately established at this time since the space program operations are not known. However, no significant problems are anticipated.

B.5 Propellant Management

The modular shuttle requires a considerable amount of plumbing between the several tanks including ducts, valves, connectors, seals, and a control system. The weight of the propellant management system for Class 3 RNS's is estimated by Lockheed to be 1,200 to 1,700 lbs more than for Class 1, depending on the number of tanks. MDAC estimates the weight increase for Class 3 to be between 1,700 and 2,400 lbs. The leak integrity of the many connectors in the Class 3 system has been questioned during the briefings, largely because quick-disconnects have generally been specified. Neither an evaluation of the severity of the problem nor possible solutions have been given, although it is a disadvantage of the modular RNS configuration.

B.6 Radiation Shield

In the earlier days of the nuclear rocket program, it was thought that the hydrogen propellant in a nuclear stage would provide almost all of the necessary shielding from the engine radiation, even though there is little or no propellant left at the end of the burn. About three years ago, however, it was found that with no shielding other than the 3,000 lb internal engine shield, the accumulated radiation dose at the crew compartment would be around 10,000 rem during one mission. The acceptable dose is about 10 rem.

Further studies of the problem indicated that at least 10,000 lbs of shielding in addition to the engine shield would be necessary. As a result, both the engine and the stage have been redesigned to reduce scattered radiation and secondary gamma radiation generated by absorption of neutrons. With the redesigned engine and stage, the estimates of external disc shield weight, still very tenuous, range from 0 to about 10,000 lbs. One of the reasons for the divergent values is the variety of stage configurations, some of which provide considerable shielding. In some analyses, for instance, the Class 3 designs are expected to require no shield other than the 3,000 lb internal engine shield. Some configurations, though, such as the standpipe or internal cell, have structural weight penalties in themselves of a few thousand pounds that are solely attributable to the need to attenuate radiation. The following table summarizes the Phase II shield weight estimates of two of the contractors:

	Class I	Class I Hybrid	Class 3
MDAC	2,800	1,900	0
NAR	∿6,000 lbs*	---	---

In Phase II and early Phase III, Lockheed did not report shield weights because they estimated that no shield was necessary in the modular configuration. However, in the second portion of Phase III,[17] they found the modular vehicle to require between 5,900 and 8,100 lbs of shielding.

---

*About 2,000 lbs of structure is also required for the internal cell. Furthermore, NAR reported radiation doses at the tank top immediately above the internal cell and did not consider the crew location.

From late 1967 to 1969 the need for radiation shielding became a major concern. Then interest decreased, and until Lockheed's very recent results, it appeared that reconfiguring the stage and engine was expected to solve the problem. It is still expected to greatly reduce radiation. This author is not sure that the exotic configurations can really reduce the radiation level by the factor of several hundred to a thousand that is necessary, and that the calculations that show the lowest radiation levels are actually the most accurate. It is possible that the radiation problem is neither solved nor accurately evaluated. The radiation transport calculations are difficult to perform because of the complex geometry in which scattering takes place, which requires that approximations be made. Approximations must also be made to the angular scattering properties of nuclei. Further, the paths of most of the radiation are quite indirect, making it impossible to intuitively guess the effect of many configuration modifications. It is noted with some concern that except for Lockheed's work during the last few months, attention to the shielding problem appears to be diminishing, as indicated by two of the three contractors not including radiation shield estimates in their weight summaries in the Phase II final briefings, and the same number omitting shielding from the Phase III interim weight estimates.

IV. NERVA ENGINE

Because the NERVA development program is not within the scope of the NFSD studies, this section is included only to provide a working knowledge of the engine, including descriptions of operation, problems limiting performance, interfaces with the stage, and estimates of weight and performance.

A. Description

The energy for nuclear propulsion is derived from a controlled, nuclear fission chain reaction in a nuclear reactor. Fissions of U-235 nuclei generate heat in the reactor fuel material. Hydrogen pumped through the reactor is heated by the fuel to temperatures of around 4200°R, and then exhausted through the rocket nozzle. The nuclear reactor, then, acts as a heat source in place of the combustion process of chemical rockets.

The configuration of the NERVA engine is shown in Figure 7. The central core region is surrounded by 12 control drums composed of sections of neutron absorbing and sections of neutron reflecting materials. (A neutron reflector does not actually reflect neutrons, it only diffuses them so that some are returned to the core region.) Control of the reactor is accomplished by rotating the drums, which changes the positions of the reflector and absorber sections, and returns more or fewer of the escaping neutrons to the core.

The core region is composed of fuel elements and tie tubes, which are structural supports for the fuel. The fuel elements are graphite with beads of uranium carbide (UC) dispersed throughout. Both the graphite, which is the moderator, and the uranium, which is the fuel, are necessary for maintaining the chain reaction.

Hydrogen is pumped through the reactor by a turbopump, which is driven by heated hydrogen. About a year ago the turbine operation was changed from a hot bleed cycle to a full-flow, or topping, cycle. In the hot bleed cycle a small fraction of the exhausting hydrogen is bled from the main thrust chamber, cooled, and then used to drive the turbine. The turbine exhaust, being at a lower temperature than the main propellant exhaust, lowers the overall Isp. With the full-flow cycle, all of the propellant is exhausted through the engine nozzle at maximum temperature and hence there is no degradation in performance resulting from the need to power the turbines. This is accomplished by using all of the propellant to regeneratively cool the nozzle and control drums of the engine, and using the heat absorbed by the propellant to drive the turbopump. The turbine exhaust then flows through the reactor core where it is heated to maximum temperature. The flow path of this cycle is shown in Figure 8.

B. Engine Performance

The specific impulse of a rocket increases as the temperature of the propellant gases increases and as the propellant molecular weight decreases. Since there is a great amount of energy available from a nuclear reactor, operating temperatures are limited only by the properties of materials of fabrication, particularly for the nuclear fuel elements, and these temperatures presently are lower than those of chemical rockets. However, the molecular weight of hydrogen is significantly lower than that resulting from combustion of hydrogen and oxygen (or any other chemical propellants), and so the propellant exhaust velocity of the nuclear rocket is much higher than that of a chemical rocket. Increasing temperature to increase exhaust velocity and Isp is a major effort in the NERVA program, but the high Isp of the present NERVA engine is due solely to the low molecular weight of the hydrogen.

The goal of the NERVA program is an engine capable of operating for 10 hours at an Isp of 825 seconds or more. This goal was established to meet the requirements of the cislunar shuttle. The present capability is estimated by the AEC to be about 4 or 5 hours at 825 seconds, which is thought to be close enough to the 10 hour goal to be economically practical. Based primarily on past progress, this author anticipates that the 10 hour goal can be met.

As will be discussed below, corrosion of the fuel limits both Isp and endurance. Since corrosion increases with temperature and operating time, the two can be traded against each other. That is, if only 1 hour of operation is necessary, an Isp above 825 seconds can be obtained. It is even likely that the Isp of a particular engine can be selected to meet the endurance requirements of its mission.

Since a nuclear reactor can be operated at any power level below its maximum, throttling of the NERVA engine is possible. The specifications call for throttling to 60% power at full Isp.

In order to maximize engine reliability, many engine components are redundant. For instance, there are two turbopumps in parallel, each capable of meeting full power requirements. The engine specifications also call for the capability for emergency operation at 30,000 lbs thrust for 20 minutes after almost any credible malfunction. It is hoped that the probability of a complete failure can be reduced to almost zero by providing for reduced power operation after any severe component or subsystem failure. The 20 minute emergency operation is sufficient for placing the RNS in a safe orbit (safe for both the crew, assuming rescue capability, and the earth population) from any point in a lunar mission.

C. Weight

The weight of propulsion (or other subsystem) is crucial to the payload performance of a transportation vehicle; the heavier the vehicle, the less it can carry with a given engine. Because of its high Isp, the nuclear rocket can be heavier than a chemical rocket and still offer significant advantages. In the last few years the estimated weight of the NERVA engine has risen from 18,000 pounds to 25,750 pounds and these reported figures do not yet include the effect of the change to the full-flow cycle. It is noted, though, that until recently, development had not been aimed at minimizing engine weight. A program now underway to reduce weight is expected to result in a reduction of about 3,000 pounds.

D. Limiting Factors

Corrosion of the graphite fuel elements by hydrogen presently limits propellant exhaust temperatures to 4200°R for operating times of 4 or 5 hours. It is conjectured that operating time at this temperature can be doubled by the time the nuclear shuttle is operational. The reduction of fuel element corrosion has been a major goal of the NERVA program for some years. Figure 9 shows the substantial progress made in this area between 1964 and 1967. The improvement is attributable to better metal carbide coatings on the graphite fuel elements.

New fuel element materials that would reduce corrosion are under development. The graphite/uranium carbide composite material is furthest along, and in fact is ready for reactor testing. At the time that composite development began, it was expected that it would corrode much more slowly than graphite with a metal carbide coating. However, work with graphite has progressed in the interim and the advantage of the composite is not as great as was originally thought. Nevertheless, it is expected that the baseline fuel will be the graphite/uranium carbide composite. Disadvantages of the composite fuel include increased weight and difficulty of fabrication.

Fuel elements of pure uranium carbide would offer temperatures of 6000°R or higher (Isp $\geq$ 950 sec) and almost no corrosion problems, but at present the difficulty of fabrication is prohibitive. It probably will be necessary to completely redesign the solid core nuclear rocket, including its general configuration, to accommodate uranium carbide fuel.

E. Stage/Engine Interfaces

Primary technical areas in which the engine interfaces with the stage include propellant thermodynamics, nuclear radiation, and aftercooling. Aftercooling primarily affects mission profiles rather than the stage configuration.

E.1 Propellant Thermodynamics

Results of Phase II of the study indicated that if small changes were made in the specified minimum propellant conditions at the turbopump inlet, then the NERVA engine could start autonomously with no prepressurization system. Consequently the thermodynamic requirements of the NERVA engine system were reevaluated, and there is no longer a need for prepressurization.

The tank pressure during nominal operation is presently specified in the NERVA Reference Data book[20] as 28 psia, but the stage contractors are allowed to specify slightly different pressures at their option. Considerably lower pressure is allowed during startup, and the limits on ingestion of vapor by the pump at low power levels have been relaxed.

E.2 <u>Nuclear Radiation</u>

The interface between engine radiation and the stage is extreme, and both engine and stage designs have been significantly influenced by the radiation problem. Calculations of either the nuclear radiation emitted from the engine or the interaction of the radiation with the stage are difficult to perform, and the accuracy of the results has not yet been established.

The NERVA engine system includes a 3000 pound radiation shield, which is adequate for unmanned operation of the RNS. Radiation attenuation is sufficient for protection of electronic and mechanical engine components and for control of propellant heating. For manned missions, however, a larger shield will probably be necessary. The additional shielding (an external disk) is considered to be part of the stage, and was discussed in Section III.B.6, Radiation Shield.

E.3 <u>Aftercooling</u>

The aftercooling requirements have relatively little impact on the stage construction, but they do affect the mission profile and the overall stage performance. Aftercooling propellant is to be supplied both in pulses and in a continuous <u>trickle flow</u> until the total heating rate in the core has decreased to about 10 KW. At this power level, the heat can be radiated to space without damage to the core. The aftercooling propellant flow is driven by the tank pressure.

Since the NERVA fuel elements are corroded (not eroded) by hot hydrogen and aftercooling uses hydrogen propellant, the core temperature must be kept well below the operating temperature. Hence, the Isp during cooldown is between 400-500 seconds. It is expected that the aftercoolant requirements will be predictable to within about 5%, so that some of the thrust from the cooldown can be factored into the mission profile and utilized. On an outbound flight, a velocity increment after departure will not be as efficient as one provided at perigee; however, during arrival at the moon or earth, the aftercoolant velocity increment can be used effectively to decelerate into a lower orbit.

V. OPERATIONS AND SAFETY

The reuse of a space vehicle gives rise to several operations not required with expendable stages, and the requirement that these operations be performed in space increases the difficulty. Nuclear propulsion further complicates in-space operations by introducing a radioactive environment.

The Phase II NFSD studies devoted relatively little effort to defining and describing the required mission operations (nominally 3% of the study). The analysis of operations stressed the mechanics of the operations with only moderate regard given to difficulties created by the radiation and the differences between operations with chemical and nuclear shuttles. That is, the discussions of mission operations contain little more than what would be required for discussing chemical shuttles, although maps of the radiation environment are given.

The on-going Phase III studies, with 20-25% of the study effort devoted to operations, still will not completely rectify this problem. Although, the work thus far (in both phases) includes estimates of the radiation environment and one or two estimates of timelines for certain operations, calculations of radiation doses have not been presented, nor have analyses regarding the feasibility of performing the various operations in the radiation environment. So far, all required operations have been assumed to be feasible. Some of the most recent analyses have indicated that very extensive calculations or space experiments may be necessary for complete understanding.

Because this author considers the NFSD treatment of orbital operations to be insufficient in many areas, a few of the comments expressed in this section go beyond the contractors work, although all calculated data is taken from the NFSD studies.

Resupply and maintenance of the RNS (or of a chemical cislunar shuttle) include the following operations: rendezvous, docking, station keeping, zero-g propellant transfer, equipment module replacement, repairs, crew transfer, payload transfer, engine removal and installation, engine disposal, prevention of unprogrammed reentry, and emergencies. Some operations such as engine removal, replacement, and disposal are severely hampered by nuclear radiation. Others, such as rendezvous, docking, and departure, require only that the specific operations be planned with attention given to radiation. The impact of the radiation environment on each of the various mission operations is discussed below. Ground operations are also discussed.

Nuclear radiation from the NERVA can be separated into two categories: that emitted during engine operation and that emitted by the fission products* after the reactor has been shut down. The radiation during operation is more intense, but the delayed radiation from the fission products continues at significant levels for years and is a substantial hazard during the time period of most of the mission operations.

The crew of the RNS is protected by a shadow shield at the engine that provides protection in a conical region of space, as shown in Figure 10. The half-angle of the cone is around 8° to 15°. It is desirable that all orbital operations external to the RNS take place inside the conical, shielded region. For any operation that cannot, such as engine maintenance or removal, either special procedures must be devised or the feasibility of the operation must be questioned.

A. Ground Operations

Prior to the first use of the engine, there are no fission products and consequently no hazardous radiation. The only source of radiation is the natural activity of the uranium, which is weak and constitutes no hazard. Therefore, ground operations that are unique to nuclear propulsion are those concerned with keeping the reactor from becoming critical (establishing a sustaining chain reaction), which would generate radioactivity. To prevent criticality, poison wires are inserted into the coolant passages of the NERVA reactor. These wires absorb neutrons and thereby prevent criticality. They are inserted after the reactor undergoes criticality tests and are removed when the engine is in orbit.

Despite the poison wires, criticality is still possible if the reactor is immersed in water or crushed by impact. Hence, a certain amount of care is still necessary in handling the reactor. Otherwise, ground operations with the nuclear shuttle are similar to those with a chemical vehicle.

---

*Fission products are the various elements that are formed when uranium fissions. They are initially radioactive, each with its own half life. The fission product radiation level is dependent upon the number of fission products generated during operation, which is determined by the integrated power, or total energy produced during operation. Also, the fission products die away with time such that the total radiation decreases approximately as 1/t, where t is the time after shutdown of the reactor.

The studies by the contractors have noted the various assembly and transportation requirements. No difficulties have been discovered, and the costs of modifying facilities to handle the large hydrogen tank are not excessive. (See Section VII, Manufacturing, Facilities, and Testing).

B. Orbital Operations

Many of the orbital operations required with the RNS have been mentioned in the briefings and final reports, but most have not been examined carefully. An attempt is made here to discuss the operations that have been studied thus far as well as those that need further attention. Particular problem areas are noted, and the feasibility of some operations is questioned. In contrast, none of the contractors has yet mentioned the possibility that some operations may not be feasible.

Before addressing individual operations, some quantitative discussion of radiation levels is necessary. The total allowable radiation dose to astronauts from all sources other than cosmic rays will probably be in the range of 10 to 25 rem per year. Analysis and design of the shield for the RNS has usually been based arbitrarily on a dose of about 10 rem to the crew during operation of the NERVA engine. Solar flares may contribute a few more. Hence, the dose allowable during operations with the RNS is a few rem, but the less radiation the better. The number of operations in which a particular astronaut is involved will also be an important factor in evaluating the operations. If an astronaut is in space for 3 months he could be involved in several resupply and rendezvous operations. Frequent encounters with radiation fields of 1 rem/hr, for instance, could add up quickly to his allowable dose. It must be realized, though, that the subject of allowable radiation doses is inherently nebulous, due largely to the absence of specific cause and effect relationships. That is, an increase in the long term radiation dose increases only the probability of contracting various diseases; no specific symptoms can be observed. A malfunction of a space system that results in a moderate increase in the dose to astronauts will have no obvious or immediate consequences.

The expected radiation field surrounding the RNS during operation is described by Figures 11 through 13, taken from Lockheed's final report.[11] Figures 13 through 18 (also from Ref. 11) describe the radiation after shutdown of the reactor, which is when most operations are carried out. The radiation levels from these graphs, together with the previous paragraph provide a basis for evaluating the operations discussed below.

B.1 Rendezvous and Station Keeping

During full power operation of the NERVA engine, the radiation level 10 nautical miles from the RNS in a lateral or rearward direction is about 25-30 rem/hr (Figure 12). If the NERVA engine were used for either rendezvous or departure from another manned spacecraft, that spacecraft would necessarily be to the side or to the rear of the NERVA engine, and hence in a high radiation field. Therefore, the contractors have concluded that the RNS reaction control system must perform the rendezvous and departure maneuvers. It is assumed that the NERVA engine can be operated only at distances of 100 nm or more from other manned spacecraft. The additional time involved in maneuvering with the RCS is only about one hour.

With the NERVA engine shut down, the effect of orientation of the RNS is still present, but the magnitude of the radiation is decreased. Rendezvous to within reasonable distances (several hundred feet), or station keeping, can be accomplished if the vehicle orientation is controlled. Poor vehicle orientation could be tolerated for short periods of time. For instance, 400 ft <u>to the side</u> of the reactor, the radiation level is about 1 rem/hr 10 days after shutdown following the tenth lunar mission (Figure 15). With the vehicle oriented properly, though, and with an external disc shield, the dose rate <u>one day</u> after shutdown is less than 1 millirem/hr 100 ft above the <u>top</u> of the reactor (Figure 17). The radiation level in a given direction is approximately inversely proportional to both the time after shutdown of the reactor and the square of the distance from the RNS.

B.2 Docking

Docking of small spacecraft, such as the space tug, with the RNS should be straightforward. However, large spacecraft that extend outside of the conical shielded region, such as the Space Shuttle, Space Station, or propellant depot, would lead to problems in two ways. First, direct radiation from the NERVA engine would endanger the crew of the other spacecraft if they were outside the shielded region. Second, unmanned portions of the other spacecraft that extend into the radiation field would scatter a fraction of the radiation into the manned areas and into the RNS crew compartment. Docking then, presents no unique problems, provided that the docked vehicle is entirely inside the shadow of the radiation shield.

B.3 Zero-g Propellant Transfer

Separation of the liquid and gaseous phases of propellant must be maintained during propellant transfer so that only liquid is transferred. The NFSD studies have identified the most attractive methods of orienting the liquid propellant in the tanker vehicle to be linear acceleration and rotation. Linear acceleration produces a substantial translation of the RNS during its refueling, but the effect can be minimized by reversing directions during the refueling. With rotation, the center of gravity of the tanker/RNS combination is continuously changing during the transfer operation. The effect of the moving mass has not been evaluated.

With the modular RNS (Class 3), refueling can be accomplished without zero-g propellant transfer by replacing the tanks instead. Although the problem of orienting the liquid is circumvented, transfers of tanks can introduce new problems. For instance, if the tanks are brought in from the side of the RNS, the nuclear radiation field would pose a hazard. Also, the frequent connecting and disconnecting of propellant lines could increase leakage. Neither of these problems has been considered carefully.

B.4 Maintenance and Repair

North American Rockwell has repeatedly emphasized that maintainability is essential to economic operation of the RNS. The other contractors have also recommended in-space maintenance and repair. Most maintenance procedures are visualized as replacement of equipment modules at the forward end of the RNS, and therefore will not be affected by the radiation environment. The considerations with this type of maintenance are those of maneuvering in space and of designing equipment for easy replacement.

Engine maintenance will present much greater problems, as will engine replacement. The radiation environment in the immediate vicinity of the RNS is severe, requiring shields on the order of 50,000 to 250,000 pounds weight for close approach of personnel. Figure 19 gives estimates of 4π shield weights necessary for close approach to a used NERVA engine. It is likely that in-space shields for engine maintenance could be lighter since they would not need to provide shielding in all directions, but it is apparent from Figure 19 that they will be heavy.

In order to avoid a heavy, portable shield, remote manipulators could be used. Since EVA is not currently favored for routine operations, remote manipulators may be required for other operations anyway. The question then becomes one of strength, complexity, radiation sensitivity, and cost of the manipulators. A robot that can be used for engine repair and replacement will be heavy and complex, and hence its development will probably be expensive. If remote manipulators are necessary only for maintenance and engine replacement, the practicality of such maintenance needs to be evaluated. Conversely, if a robot system is necessary to assemble the modular shuttle, the additional requirement to provide for maintenance may be small.

So far descriptions of the actual maintenance procedures have been limited to replacement of modules. Major engine maintenance such as turbopump replacement, is likely to be considerably more complex. This author believes that more detailed studies should be made before concluding that either engine maintenance or engine removal are feasible in space. Both operations require strength and dexterity in a hostile radiation environment.

B.5 Engine Disposal

The most desirable method of disposing of an engine at the end of its life is to send the RNS on an unmanned, one-way mission to deep space. If this should be impractical, perhaps due to lack of a useful mission or a desire to make further use of the stage with a new engine, it has been suggested that a small propellant tank and a guidance system might be attached to the engine to permit it to fly itself to deep space or a very long-lived earth orbit. In the Class I hybrid and some of the Class 3 designs, a small tank is already attached to the engine, providing a convenient propulsion module that might be used for this purpose.

Nominal end-of-life disposal does not seem to be difficult, but problems arise when an engine is not operable due to failure or some other unforeseen hazard. In this case, a space tug or other small propulsion system would be required to carry the used engine away. If the auxiliary propulsion vehicle were not retrieved, there would be an addition to the cost of disposal. The size of the disposal propulsion vehicle would depend upon whether it is to return to low earth orbit and upon whether the nuclear engine is to be removed from its stage prior to disposal.

In earlier studies of nuclear rocket interplanetary missions, a safe initial orbit for a subsequently aborted nuclear mission was assumed to be one with a lifetime of a few years or more. On interplanetary missions, nuclear engine operating time, and hence radioactivity, accrue only as the vehicle moves farther from earth and into a longer-lived safer orbit. In contrast, the NERVA engine in a reusable lunar shuttle application may be in the vicinity of the earth after operating for several hours. Lockheed estimates the necessary lifetimes of abort disposal orbits to be about 135 years after one round trip lunar mission, and 165 years after 2 round trip lunar missions, based on a dose rate of 10 rem per year, one meter from a single fuel element. Routine disposal should require even longer lifetime orbits, or preferably disposal to heliocentric orbit. In the most recent portion of Phase III, North American recommended using the space tug to deliver the NERVA engine to a circular orbit with an altitude of at least 660 nm (no lifetime was given). These orbits are substantially different from the 5 year orbit previously assumed to be acceptable for emergency disposal.

The increase in required orbit lifetime has another aspect. It is conceded that reliability of the NERVA will be lowest during transients, particularly startup. That is, one of the most likely places for failure is in the parking orbits. An orbit altitude of 270 nm that is typical of a space station logistics orbit had been viewed with approval by the nuclear community because it was thought to provide a sufficient orbital lifetime for safe abort of the nuclear engine. It now appears that this is true only at the beginning of the first mission of an RNS. However, substantially increasing the altitude of parking orbits is precluded by the Van Allen belts.

B.6 Emergency Operations

The NFSD contractors have devoted little effort to emergency operations and malfunctions. Without going into a comprehensive discussion of in-space emergencies, this section presents the authors' opinions regarding some potential emergencies that are of interest and presents brief descriptions of the problems.

Nuclear systems, more than chemical propulsion vehicles, have the ability to involve the general population of the earth in a space accident. Dangers to the earth's population can range anywhere from slight environmental contamination to injury and death caused by the impact and/or radiation from a nuclear reactor falling in a populated area.

The emergency problems and procedures that should receive more attention in the nuclear shuttle studies include the following:

- prevention of return to the earth's surface
- disposal of a disabled or structurally damaged engine
- disassembly of the NERVA engine
- low speed collision with other spacecraft (e.g., during docking)
- temporary gross error in vehicle attitude during rendezvous
- failure of propulsion system (has received attention).

Prevention of return of the NERVA engine to the earth's surface should be a basic rule in nuclear propulsion planning. In an emergency, however, an earth impact limited to deep ocean disposal should be relatively harmless. Further study is needed to establish the tradeoff between technical complexity and reliability, and the cost of improving safety.

In-space disposal of a disabled engine probably will require use of a space tug, possibly in an expendable mode. A worse problem, though, would be an exploded or a disassembled NERVA engine which could result in the random reentry of large pieces of radioactive material. One possible cause of such damage is failure of the aftercooling system. Because of the high temperature characteristics of the fuel, its chances of surviving atmospheric reentry are quite good. The implications of structural damage or partial disassembly would be of interest in regard to the safety of both the general population and the astronauts. It would appear, then, that the probability of engine disassembly should be analyzed.

The possibility of involving populated areas on earth may sometimes tend to overshadow the hazard to the astronauts in the case of malfunctions, but in evaluating the overall merit of the nuclear shuttle, safety of the crew cannot be neglected. In addition, emergencies not involving radiation must also be considered, such as collisions and functional failures.

The nuclear shuttle definition study thus far has not considered the area of emergency operations. Safety and reliability have been addressed, but the emphasis has been on preventing incidents rather than on evaluating the probability and the effect of their occurrence.

VI. RELIABILITY

At present only reliability specifications and design goals have been discussed, largely because of the difficulty of analyzing a system yet to be designed. Complicating any detailed analysis is the fact that safety requirements, even of a tentative nature, have not been set for either astronauts or the general population.

The reliability goal for the NERVA engine is 0.995 probability of no functional failures per mission. The engine is designed throughout for high reliability, including many redundant components. Also, the capability for an emergency mode of operation is planned, in which the engine would operate for 20 minutes at 30,000 lb thrust (instead of the nominal 75,000 lbs) after almost any credible failure. This emergency operation would permit the RNS to reach a suitable orbit for rescue of the crew.

NAR presented a breakdown of component reliabilities that is intended to represent the most economical means of achieving the required overall reliability. When the calculated reliability requirements of a few components were compared with predicted reliabilities (based on S-II data), it was found that the required reliabilities should be readily obtainable.

Lockheed also presented some reliability data in their final report, including a comparison of the multiple and single tank concepts. The values of reliability that are given are predictions for the propulsion system based on experience with aerospace systems. The single tank concept has a higher predicted reliability and a lower weight penalty for a selectively redundant propulsion system than the multiple tank concept. Reliability of a selectively redundant propulsion system for a Class 1 vehicle is estimated at around 0.997 for a single mission. The probability of completing 10 missions with no replacement of primary components is around 0.97. According to Lockheed, the propulsion system appears to be adequately reliable for lunar shuttle service.

VII. MANUFACTURING, FABRICATION, FACILITIES, AND TESTING

Evaluations of the ground facilities necessary for manufacturing and fabricating the RNS were presented in great detail in the NAR final briefing and final report, and in the MDAC final report. Manufacturing techniques and flow sequences were also reported but will not be recapitulated here.

North American Rockwell considered several existing facilities for construction and test of the Class 1 RNS and concluded that the ones of interest are NAR's Seal Beach facility, Kennedy Space Center (KSC), Michoud, and the Mississippi Test Facility (MTF). Manufacturing and assembly were found to be most easily accomplished at Seal Beach, although the use of Michoud is not unreasonable. A single location was recommended for cold flow tests and acceptance tests. MTF would require the least modifications, but when operations costs are included, the use of KSC is less expensive. Also, since MTF is to be deactivated, use of that facility for the RNS would incur additional costs.

Transportation of the stage from Seal Beach, California to MTF or KSC was found to pose no problems, except that the NERVA engine must be shipped separately. The same procedure as used for the S-II would be applicable (transportation by sea). Transportation from MTF to KSC is considered to be significantly cheaper by water than by land.

McDonnell Douglas evaluated the cost of manufacturing the components and subassemblies of the Class 1 RNS at Huntington Beach, California (MDAC) and assembling the stage at Michoud, La., Seal Beach, or Huntington Beach. The cost of tooling and facility modifications were found to be cheaper at Michoud or Seal Beach.

The manufacturing and transportation of the RNS appears to pose no unique problems nor require any new technologies. Furthermore, there appears to be little difference between the RNS requirements and those of a chemical stage, with the exception of the NERVA engine and its safety and test requirements. Even though production costs are important at this stage of the RNS studies, this author feels that other areas require relatively more attention to bring all aspects of the RNS to about the same level of understanding. It is felt that the manufacturing aspects have been over-studied in comparison with other areas, and continued emphasis in Phase III is unwarranted.

VIII. COSTS

The contractors were required to present costs for development of the RNS (including flight tests) and for an operational program including a specific mission schedule provided by MSFC. The MSFC baseline operational program, shown in Figure 20, runs from 1980 to 1989, inclusive, and involves roughly 155 cislunar shuttle flights, or about 15 vehicles. In the last few months, MSFC also required the contractors to include mission schedules with 2, 4, 6, 8, and 10 flights per year, but no results based on the reduced traffic model have yet been reported. The remainder of this section therefore is based on the 15 flights/year model.

The development, production, and total program cost estimates of the three contractors are summarized in Table 5. It is noted that all cost estimates do not include the same items, and so comparisons among the three estimates are not straightforward. Ground rules that are used consistently include the following:

1. NERVA engine development cost is not included.

2. NERVA engine production cost is $13 million per unit.

3. The costs of procurement and delivery of the RNS payload to orbit are not included.

4. Contractor's fee and NASA administrative expenses are not included.

A. Development Costs

The differences in development costs are largely due to the flight test, which is not accounted for similarly in all studies. Lockheed included the entire cost of the first flight test in the development cost, while MDAC did not include orbit delivery costs for either the RNS or its propellant. North American charged 20% of the flight test to development and 80% to the operational program, using the assumption that the vehicle would be available for service after testing. Allowing for these differences in the ground rules, the Lockheed and MDAC estimates for development are similar and NAR's estimate is considerably higher.

B. Operational Costs

McDonnell Douglas included only production, testing, and launch preparation in their estimates of recurring costs. The cost of transportation to orbit, which is most of the operational cost, was not included. Consequently their $1.59 billion estimate of "total" costs does not really represent total program costs. The production cost of $61 million per vehicle, with engine, (Class 1 or Class 3) is in agreement with Lockheed.

Lockheed's estimates of total program costs are much higher than MDAC's -- around $8.7 billion for Class 1 and $9.0 billion for Class 3. Earth-to-Orbit transportation is included at $5 million per Space Shuttle flight, and $167 million per Saturn V flight. (The Saturn V is used only for delivering the Class 1 RNS to orbit.) In contrast to the 10 mission life usually assumed for the RNS, Lockheed assumed each RNS is useful for about 30 missions, with engine replacement every 10 missions.

North American Rockwell outlines a requirement for 19 nuclear shuttles and 6 large propellant tanks for a total of 25 Saturn V launches. A Space Shuttle cost of $7 million per flight and an RNS production cost of $84 million/RNS (with engine), both higher than the values reported by Lockheed, are assumed.

IX. CONCLUSIONS AND COMMENTARY

The main conclusion of the NFSD contractors is that the technology is well in hand for developing and operating a nuclear cislunar shuttle. They recommend that future work include further study of orbital operations, development of more detailed payload and mission requirements, and evaluation of the appropriate influence of Space Shuttle and RNS designs on each other.

In general the studies are well done and are an excellent base for more extensive work that will provide a basis for making decisions concerning nuclear powered space transportation. Nevertheless, the studies cannot effectively cover every question that arises and so some attention must be given to the priority of investigation. With this consideration in mind, several comments are offered regarding study emphasis that may be useful in directing the course of future studies. These comments are based on two related considerations:

1. At the completion of the study, all areas should be at about the same level of understanding, except for a few difficult problems that would require inordinate amounts of time to solve.

2. Because of the greater experience with chemical rockets and because chemical rockets are an alternative to the RNS, the NFSD studies should highlight the problems and benefits unique to nuclear propulsion.

The ground rules of the NFSD study specify that the RNS should be sized to meet the cislunar payload requirement of the Integrated Plan: 119,000 pounds from earth orbit to lunar orbit with empty return of the RNS to low earth orbit. All contractors sized the RNS for this payload capability on missions with moderate plane change requirements. However, if the maximum payload capability is necessary only for occasional missions such as delivery of space stations, then these few missions could be scheduled to minimize plane changes. Hence it might have been appropriate to size the RNS for the 119,000 lb payload using less demanding trajectories, assuming that the 119,000 lbs is the maximum, and not the usual requirement. Although it is the nature of the study to select and evaluate a fixed-size stage, some data on other sizes of stages would be interesting in future studies. MDAC included some data on larger stages, but none of the contractors studied smaller ones. It is possible that smaller stages could be economical with a less ambitious traffic model.

Stage and subsystem construction are generally well presented in the NFSD reports and the descriptions provide a useful framework for discussing both configuration and subsystem alternatives. However, the data on two of the subsystems, meteoroid shielding and radiation shielding, is weak. These areas are plagued by a lack of accurate calculation techniques or input data, and accurate design estimates are extremely difficult to make. It is felt that the uncertainty is more serious in regard to the radiation shielding, where the most optimistic results are being accepted and attention to the problem is diminishing.

Work on the Class 3 vehicles (multiple tank) has identified several possible configurations. However, two major problems have not been considered: leakage from the many seals, valves, and connectors; and the general operational complexity of assembling a large rocket in orbit.

To date the work on orbital operations has identified the required operations and the environment of the RNS. The difficult operations, such as engine maintenance, engine replacement, and engine disposal, have been identified but not in depth. The NFSD study has assumed that any operations that are desirable can be carried out. This author, however, questions the feasibility and the expense of building a large spacecraft that can be remotely assembled and disassembled in orbit, especially if such sophistication is only to permit engine maintenance or engine replacement. Further study should be made of configuration and operational concepts that do not require engine maintenance and that minimize maintenance external to the crew compartment.

Rendezvous and docking of the RNS involves a number of operational restrictions. For example, the studies have shown that the NERVA engine cannot be operated within about 100 miles of another manned spacecraft because of the radiation hazard. They have also noted that docking of the RNS with a large space vehicle such as a space station <u>may</u> not be possible, and hence a space tug may be necessary for ferrying all personnel and material to and from the RNS. The latter aspect of rendezvous and docking has been presented as a possibility, but a comprehensive analysis of all the implications or the modes of operation has not yet been made. Although further definition of operational problems will be difficult, it is nonetheless necessary.

The manufacturing, fabrication, and testing procedures were evaluated in depth by the contractors and some discussions go into great detail as to construction procedures. The work is of value in determining cost estimates and time schedules, but because it was fairly well understood at the start of the contract, the depth and completeness of study (particularly in the NAR study) surpasses those of other areas. Continued strong emphasis in Phase III does not appear to be warranted until other areas of the study can be brought to an equivalent level of understanding.

The latest portion of the Phase III study (September to December, 1970) was very appropriately directed to some of the areas that are least understood, such as orbital assembly of the modular vehicle, maintenance, radiation shielding, and engine disposal.

1013-DJO-klm

D. J. Osias

REFERENCES

1. "An Integrated Plan for Space Utilization and Exploration for the Decade 1970-1980," National Aeronautics and Space Administration, July, 1969.

2. "Nuclear Flight Systems Definition Study, First Interim Briefing," Lockheed Missiles & Space Co., LMSC-A959133, October 6, 1969.

3. "Nuclear Flight Systems Definition Study, First Interim Briefing," McDonnell-Douglas Astronautics Company, MDC-G0209, October 8, 1969.

4. "Nuclear Flight Stage and Payloads Study, Phase I Review," North American Rockwell, PDS69-101, October 7, 1969.

5. "Nuclear Flight Systems Definition Study, Second Interim Briefing," McDonnell-Douglas Astronautics Company, MDC-G0247, January 27, 1970.

6. "Nuclear Flight Stage and Payloads Study, Interim Phase II Review," North American Rockwell, PDS70-207, January 28, 1970.

7. "Nuclear Flight Systems Definition Study, Second Interim Briefing," Lockheed Missiles and Space Co., LMSC-A965254, January 29, 1970.

8. "Nuclear Flight Systems Definition Study, Final Briefing," Lockheed Missiles and Space Company, LMSC-A986323, May 19, 1970.

9. "Nuclear Flight Systems Definition Study, Phase II Final Briefing, Reusable Nuclear Shuttle Concepts," McDonnell Douglas Astronautics Company, MDC G0594, May, 1970.

10. "Nuclear Flight Systems Definition Study, Final Phase II Review," Space Division, North American Rockwell, PDS70-223, May 19, 1970.

11. "Nuclear Flight Systems Definition Study, Phase II, Final Report," Lockheed Missiles and Space Co., LMSC-A986223, May 1, 1970.

12. "Nuclear Flight System Definition Study, Final Report," McDonnell Douglas Astronautics Company, MDC-G0585, May, 1970.

13. "Nuclear Flight System Definition Study, Phase II Final Report," Space Division, North American Rockwell, SD70-117-5, August, 1970.

14. "First Interim Briefing, Nuclear Shuttle Definition Study, Phase III," McDonnell Douglas Astronautics Company, MDC G0671, September 2, 1970.

15. "Nuclear Shuttle System Definition Study, Phase III First Interim Review," Space Division, North American Rockwell, PDS70-242, September 2, 1970.

16. "Nuclear Shuttle System Definition Study, Phase III, Performance Review," Lockheed Missiles and Space Company, LMSC-A976106, September 3, 1970.

17. "Nuclear Shuttle System Definition Study, Phase III, Performance Review," Lockheed Missiles and Space Company, LMSC-A981482, December 17, 1970.

18. "Second Interim Briefing, Nuclear Shuttle Definition Study, Phase III," McDonnell Douglas Astronautics Company, MDC-G0747, December 16, 1970.

19. "Nuclear Shuttle System Definition Study, Phase III, Second Interim Review," North American Rockwell, SD-70-644, December 16, 1970.

20. Osias, D. J., "Performance Comparison of Nuclear and Chemical Lunar Shuttles," Bellcomm Memorandum for File, August 14, 1970.

21. Johnson, C. E., and M. H. Skeer, "The Effect of Meteoroid Shielding on In-Space Stage Performance," Bellcomm TM70-1013-2, March 10, 1970.

22. The Natural Environment and Physical Standards for the Apollo Program and the Apollo Applications Program, M-DE8020.008C, SE015-001-1B NASA, July 10, 1969.

TABLE 1

LOCKHEED WEIGHT STATEMENTS

Items	Single Tank	Multiple Tank Baseline	Multiple Tank Alternate	Multiple Tank Advanced
Structure	24,812	28,247	28,391	28,075
Insulation	1,950	3,370	2,464	2,920
Meteoroid Shield	6,560	6,052	4,844	5,198
Electrical System	660	660	660	660
Navigation, Guidance & Control System	340	340	340	340
Reaction Control System	1,690	1,630	1,252	1,585
Communication System	289	289	289	289
Data Management	238	319	278	278
Propellant Management	620	2,365	1,843	1,843
Engine System (75K NERVA)	25,750	25,750	25,750	25,750
Subtotal	62,909	69,022	66,111	66,938
10% Contingency	6,291	6,902	6,611	6,694
	69,200	75,924	72,722	73,632

BASELINE AND ADVANCED CONCEPTS USE 15' X 60' MODULES

ALTERNATE CONCEPT USES 22' X 40' MODULES

TABLE 2

WEIGHT STATEMENT (LB)

MULTIPLE MODULE RNS - CLUSTERED CONFIGURATION

Configured for 15' Dia X 60' EOS Cargo Hold

ITEM	SYSTEM	PROPULSION MODULE	COMMAND & CONTROL MODULE	PROPELLANT MODULE	TOTAL (1-1-8) CONFIGURATION
	LH_2 CAPACITY	5,100	0	3,400	277,100
STRUCTURE		1,080	610	3,810	32,170
THERMAL/METEOROID		410	---	1,800	14,810
PROPELLANT HANDLING		230	---	370	3,190
PREPRESSURIZATION		---	490	---	490
SECONDARY PROPULSION		230	2,140	---	2,370
ASTRIONICS		60	2,860	60	3,400
NERVA		25,750	---	---	25,750
TOTAL DRY WEIGHT		27,760	6,100	6,040	82,180
RESIDUALS		600	---	210	2,280
OPERATIONAL WEIGHT		28,360	6,100	6,250	84,460

OPERATIONAL WEIGHT ADJUSTED TO 300,000 LB LH_2 = 88,690 LB

TABLE 3

MDAC RNS CLASS 1 WEIGHT STATEMENT (LB)

ITEM	SYSTEM	STANDARD	HYBRID		
			PROPELLANT MODULE	PROPULSION MODULE	TOTAL
	LH_2 CAPACITY, LB	300,000	(300,000)	(9,700)	309,700
STRUCTURE		47,860	33,650	1,360	35,010
THERMAL/METEOROID		8,480	8,180	660	8,840
PROPELLANT HANDLING		970	560	230	790
SECONDARY PROPULSION		1,290	2,670	230	2,900
ASTRIONICS		3,340	3,100	60	3,160
SHIELD		2,800		1,900	1,900
NERVA		25,750		25,750	25,750
TOTAL DRY WEIGHT		90,490	48,160	30,190	78,350
JETTISON INTERSTAGES AND THRUSTERS		-19,000	-6,450		-6,450
PROPELLANT RESIDUALS		10,010	9,610	770	10,380
OPERATIONAL WEIGHT		81,500	51,320	30,960	82,280
PROPELLANT MASS FRACTION, λ'		0.788		0.790	

TABLE 4

NAR MODULAR/SINGLE TANK RNS WEIGHT COMPARISON

ITEM	INTEGRAL TANK - 33 FT DIA ELLIPTICAL AFT BULKHEAD		MODULAR CONFIGURATION
	(EARLY)	(ADVANCED)	(ADVANCED)
STRUCTURE	29,765	27,185	21,410
THERMAL/METEOROID PROTECTION	12,195	10,960	12,990
NERVA ENGINE	25,750	25,750	25,750
AUXILIARY PROPULSION SYSTEMS	10,325	10,325	15,650
EQUIPMENT	3,785	3,785	6,120
MODULAR ASTRIONICS UNIT	8,960	8,390	8,340
DOCKING SYSTEM	1,100	1,100	--
PROPELLANT RESIDUALS	5,720	5,720	3,195
WEIGHT PRIOR TO ENGINE IGNITION LESS USABLE PROPELLANT	97,600	93,215	93,455
INTERSTAGE	14,590	5,210	--
USABLE PROPELLANT	287,710	287,710	286,805
GROSS WEIGHT (LB)	399,900	386,135	380,260

TABLE 5. COST SUMMARY

CONTRACTOR	TANK CONFIGURATION	DEVELOPMENT COST	PRODUCTION COST PER VEHICLE	TOTAL PROGRAM COST
LMSC	single	$1,106 million	$61 million	$8,700 million
	multiple	986	62	9,000
MDAC	single	833*	61	1,690**
	multiple	675*	61	1,530**
NAR	single	1,250***	84	21,200
	multiple	1,710***	--****	16,800

*Cost of placing the flight test vehicle in orbit is not included

**Cost of transportation to orbit not included

***Includes 20% of cost of launching test article. Remaining 80% is charged to operation program

****Total production costs are about 3/4 of those for Class 1, but different stage lifetimes are assumed. Estimate of costs per vehicle not given.

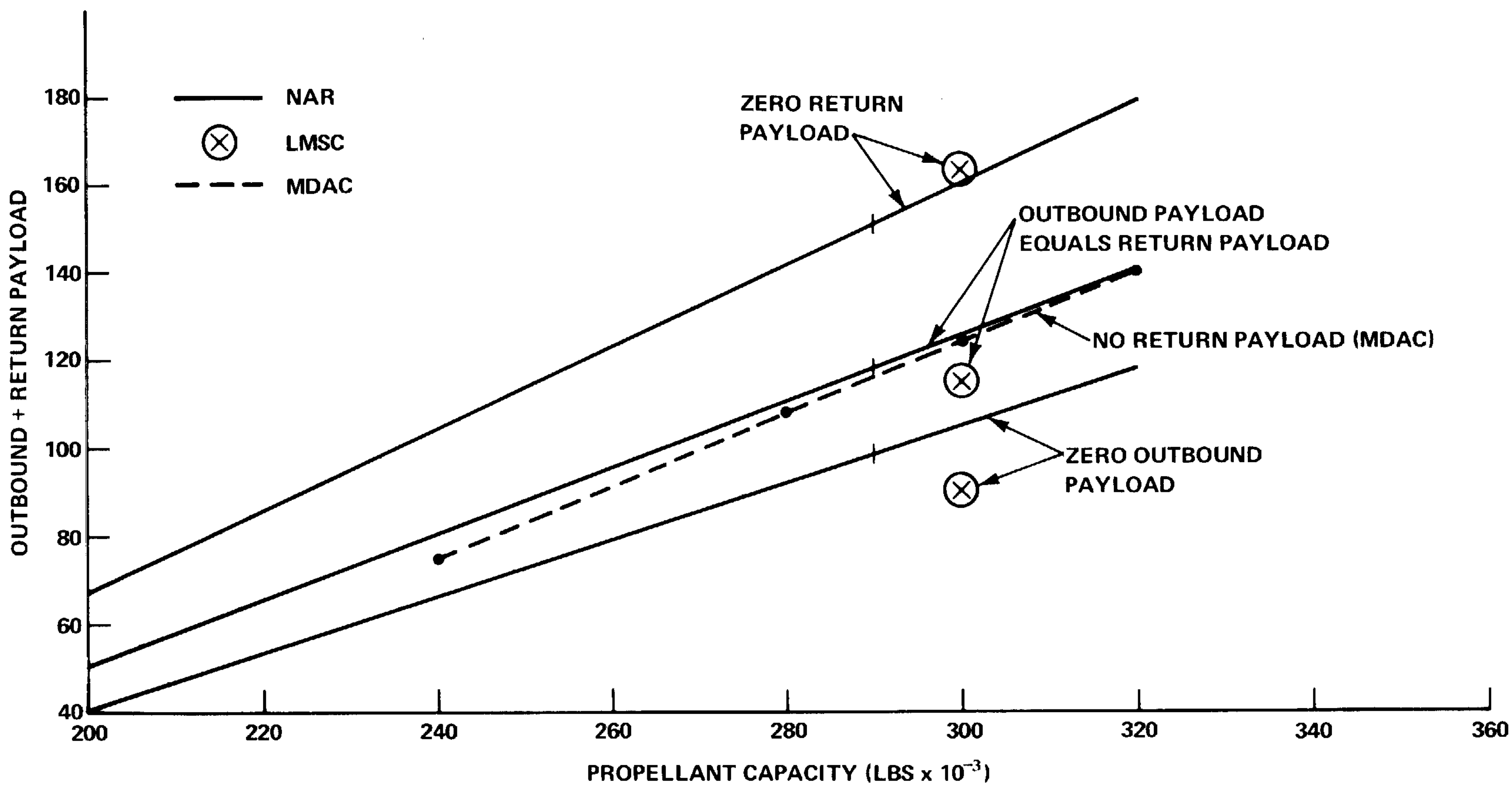


FIGURE 1 - LUNAR SHUTTLE PERFORMANCE

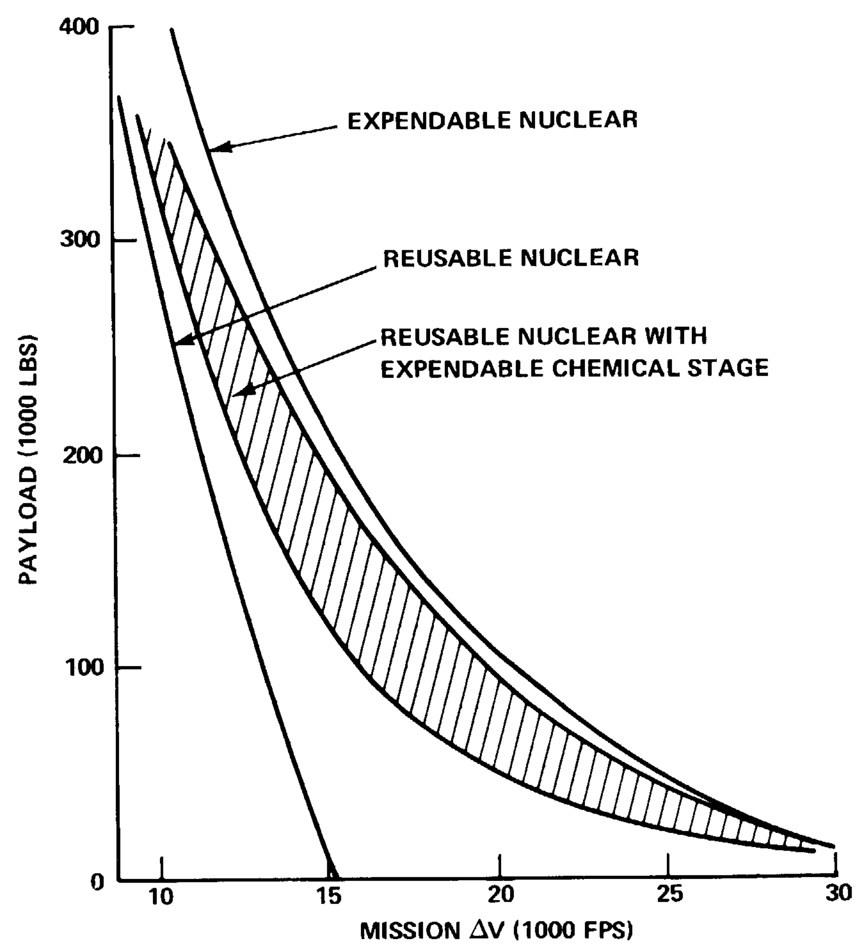


FIGURE 2 - RNS INJECTION STAGE CAPABILITY

SOURCE — NAR

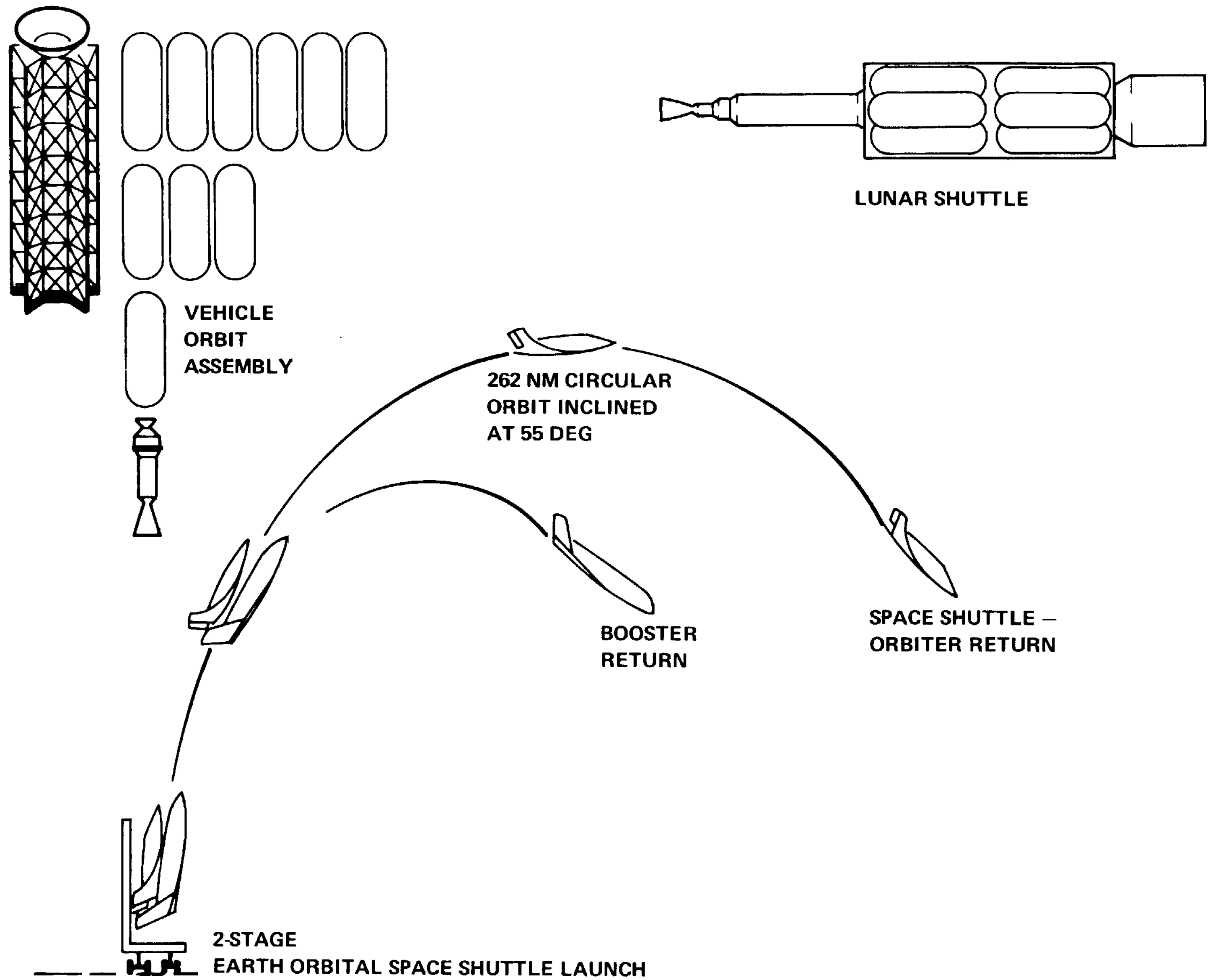


FIGURE 3 - MULTIPLE TANK OPERATIONS PROFILE

SOURCE – LMSC

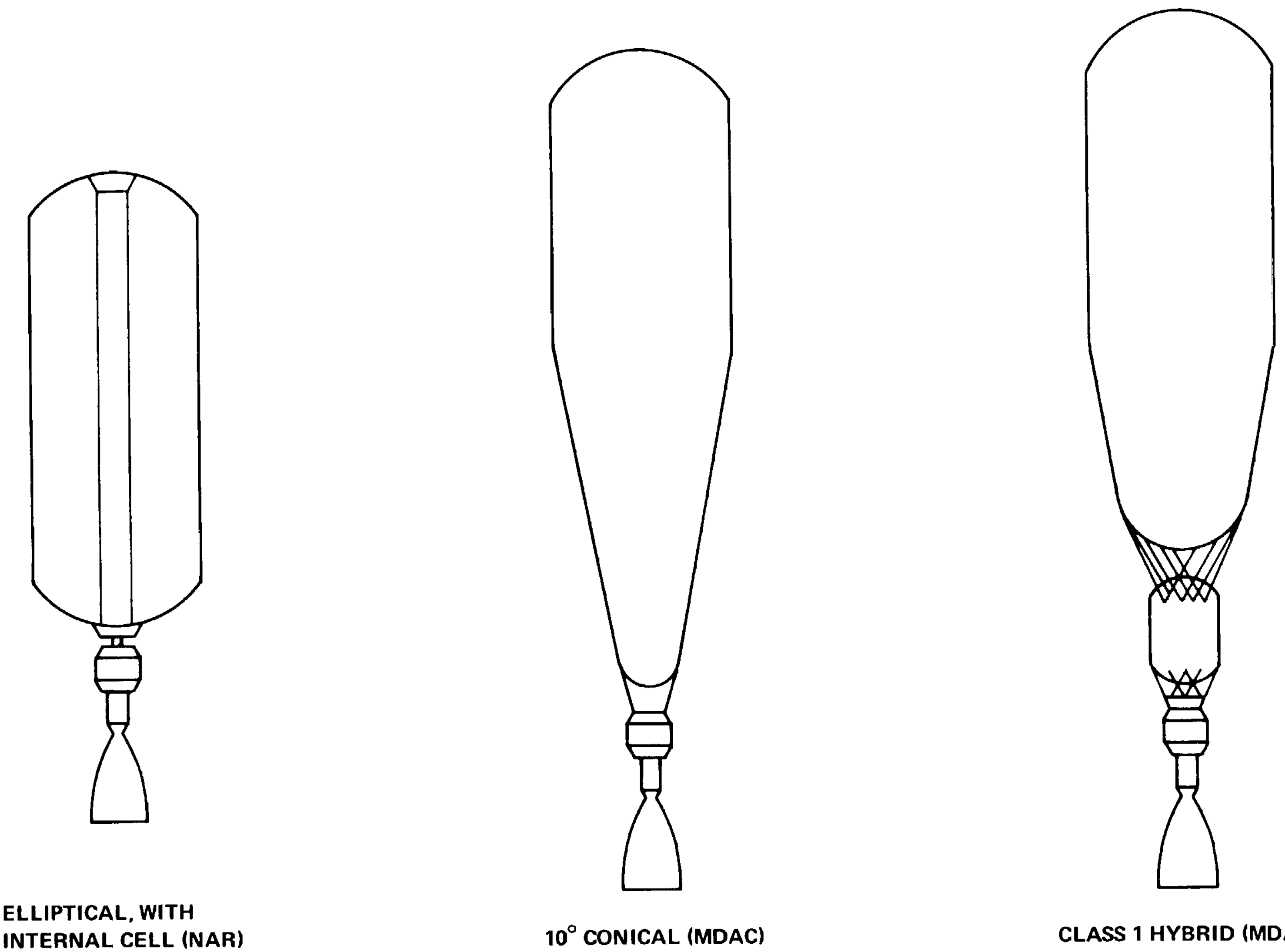


FIGURE 4 - CLASS 1 CONFIGURATIONS

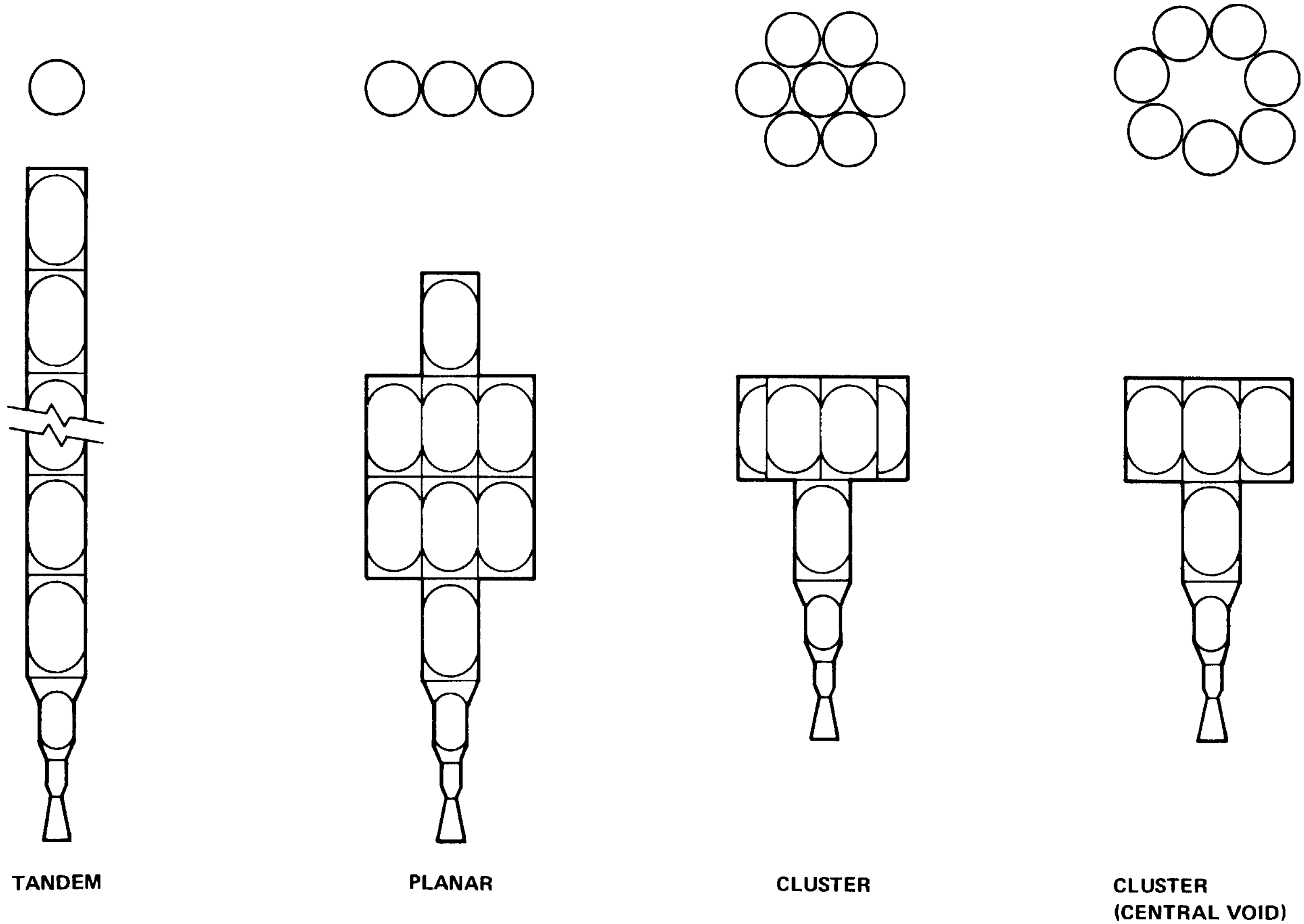


FIGURE 5 - MULTIPLE MODULE CONFIGURATION CANDIDATES

SOURCE – MDAC

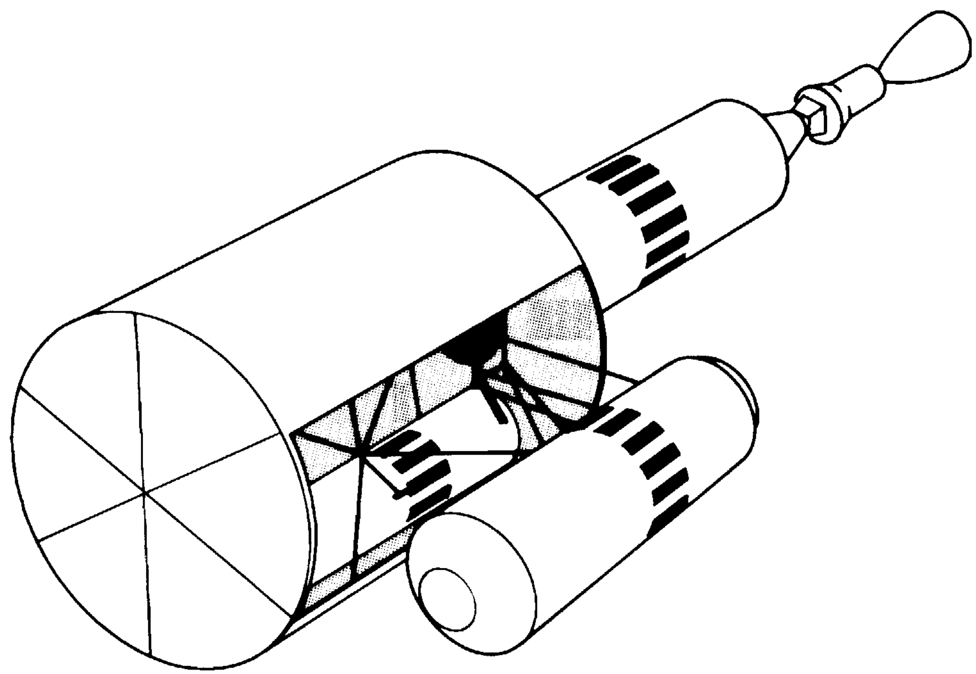


FIGURE 6 - MODULAR SHUTTLE WITH UNINSULATED TANK MODULES

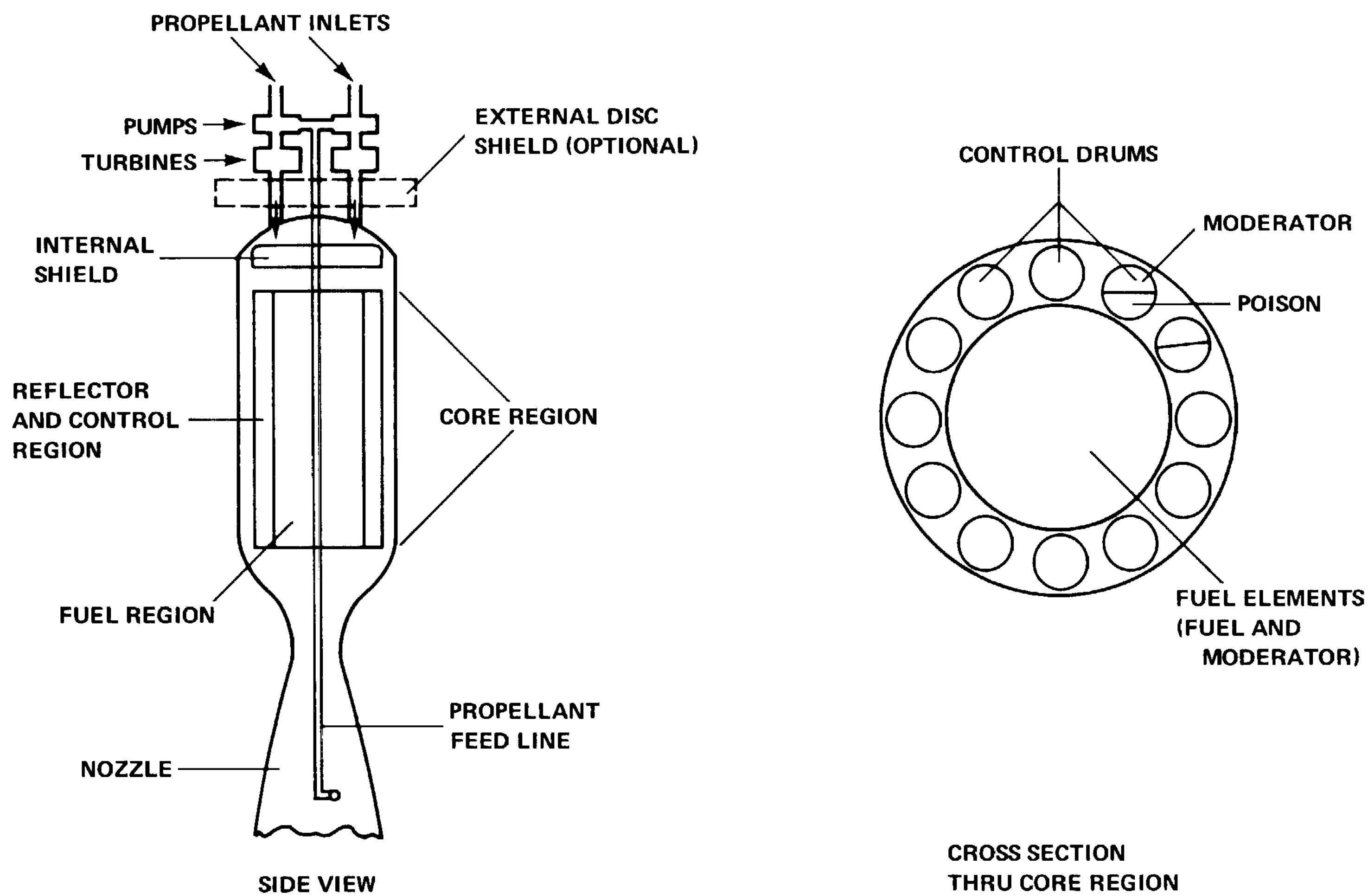
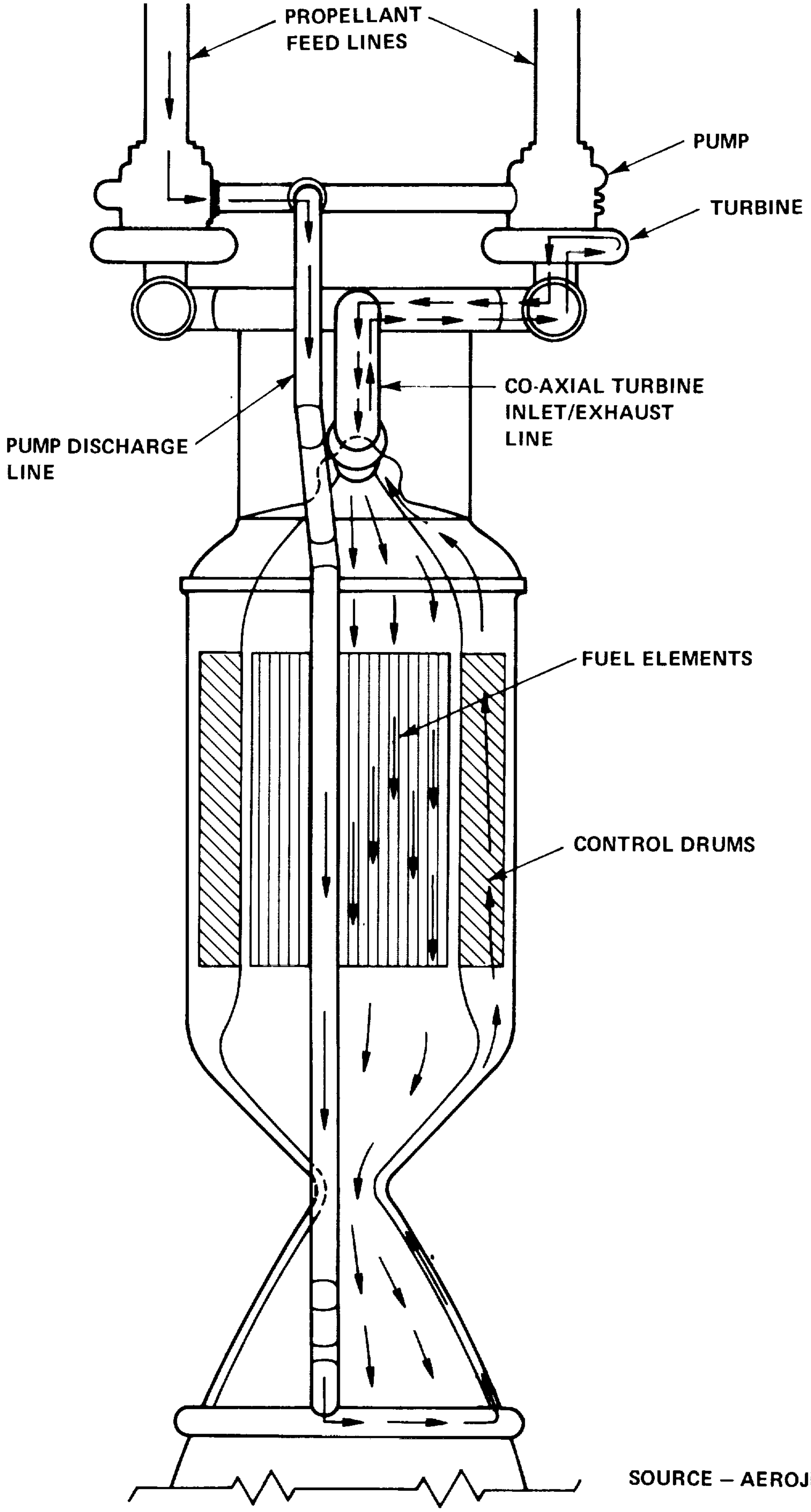


FIGURE 7 - NERVA ENGINE CONFIGURATION



SOURCE – AEROJET

FIGURE 8 - FLOW SCHEMATIC, FULL-FLOW ENGINE

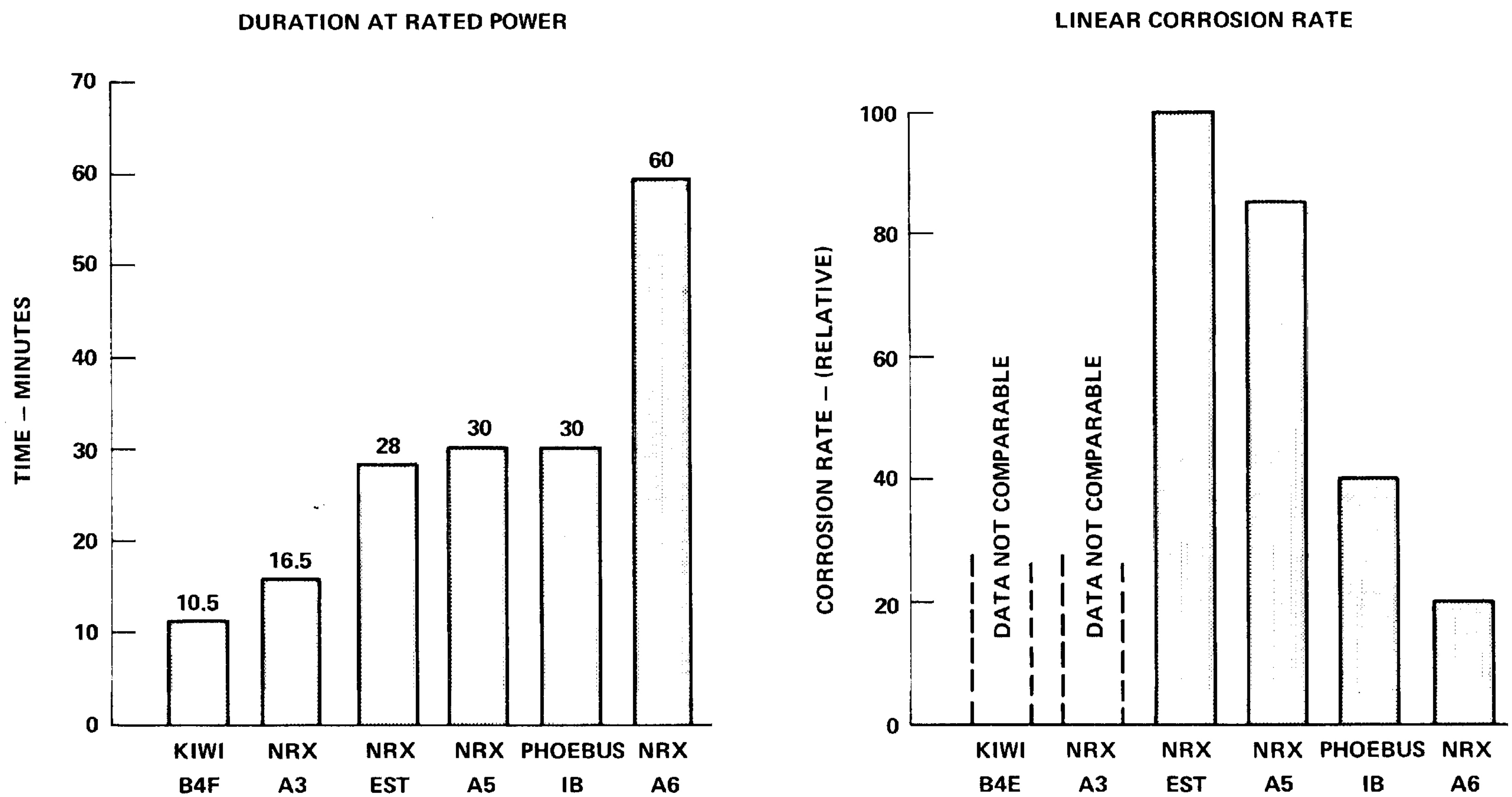


FIGURE 9 - DURATIONS AND CORROSION RATES IN REACTOR TESTS

SOURCE – AEC

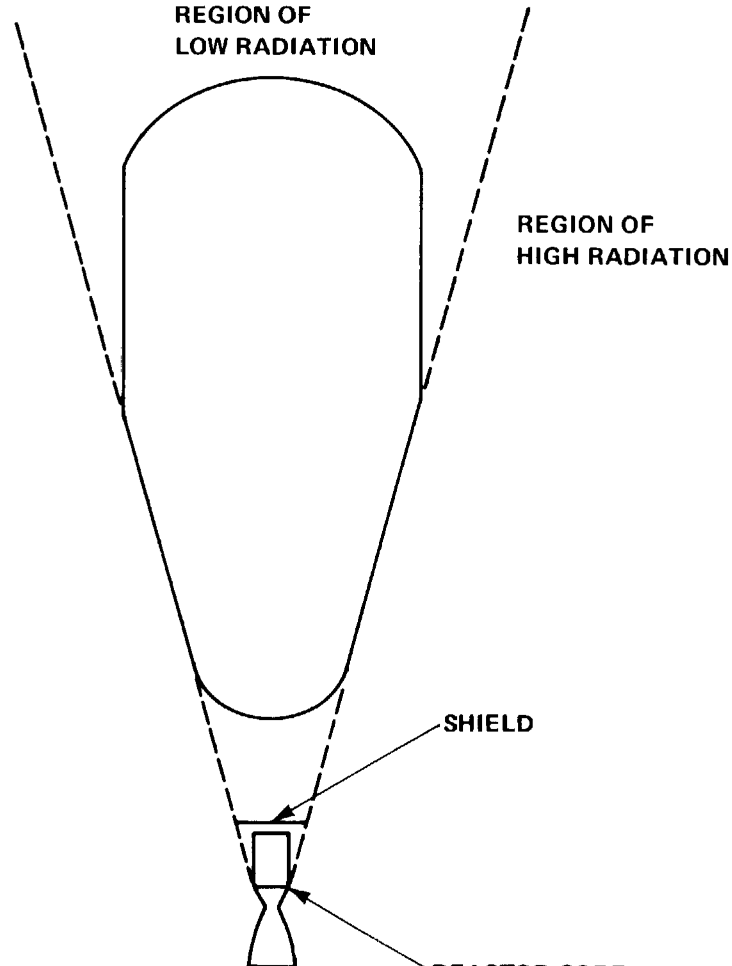


FIGURE 10 - SHADOW SHIELDED NUCLEAR SHUTTLE

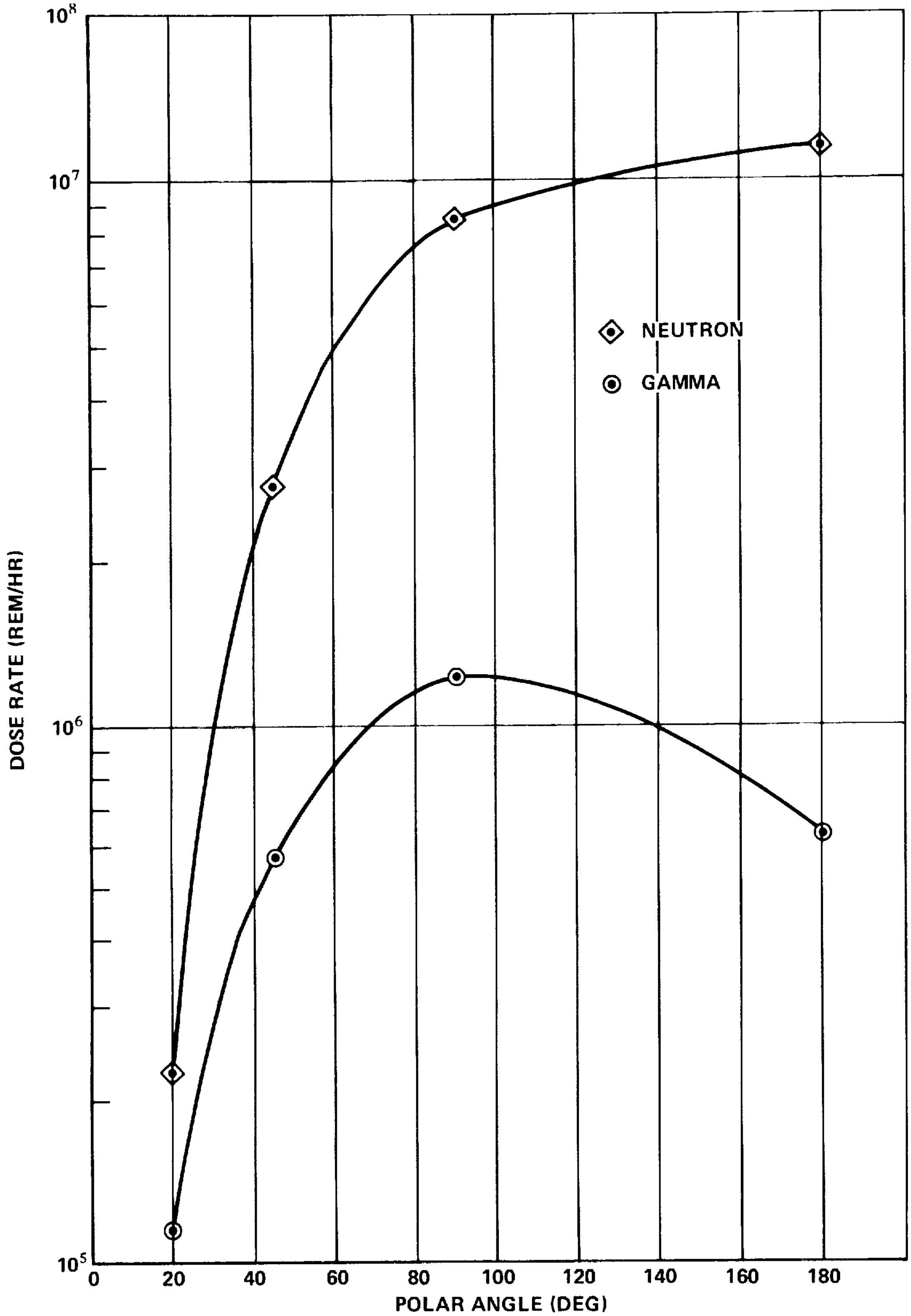


FIGURE 11 - 100 FT MERIDIAN RING DATA FOR OPERATING NERVA I WITH NO LH_2 IN TANK OR DISC SHIELD ON REACTOR

SOURCE – LMSC

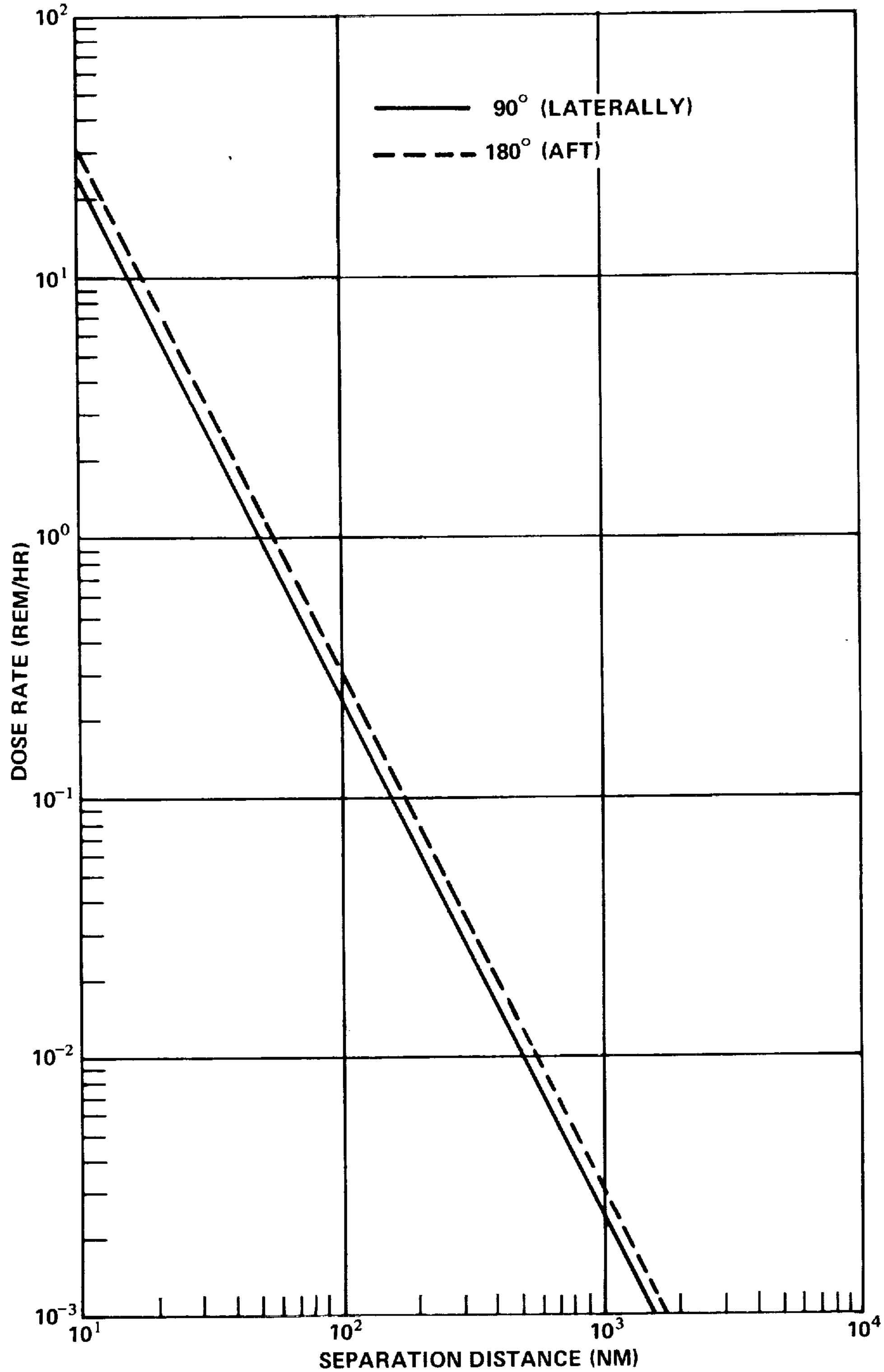


FIGURE 12 - DOSE RATE ($\eta + \gamma$) VS SEPARATION DISTANCE FOR OPERATING NERVA WITH NO LH_2 IN TANK OR DISC SHIELD

SOURCE – LMSC

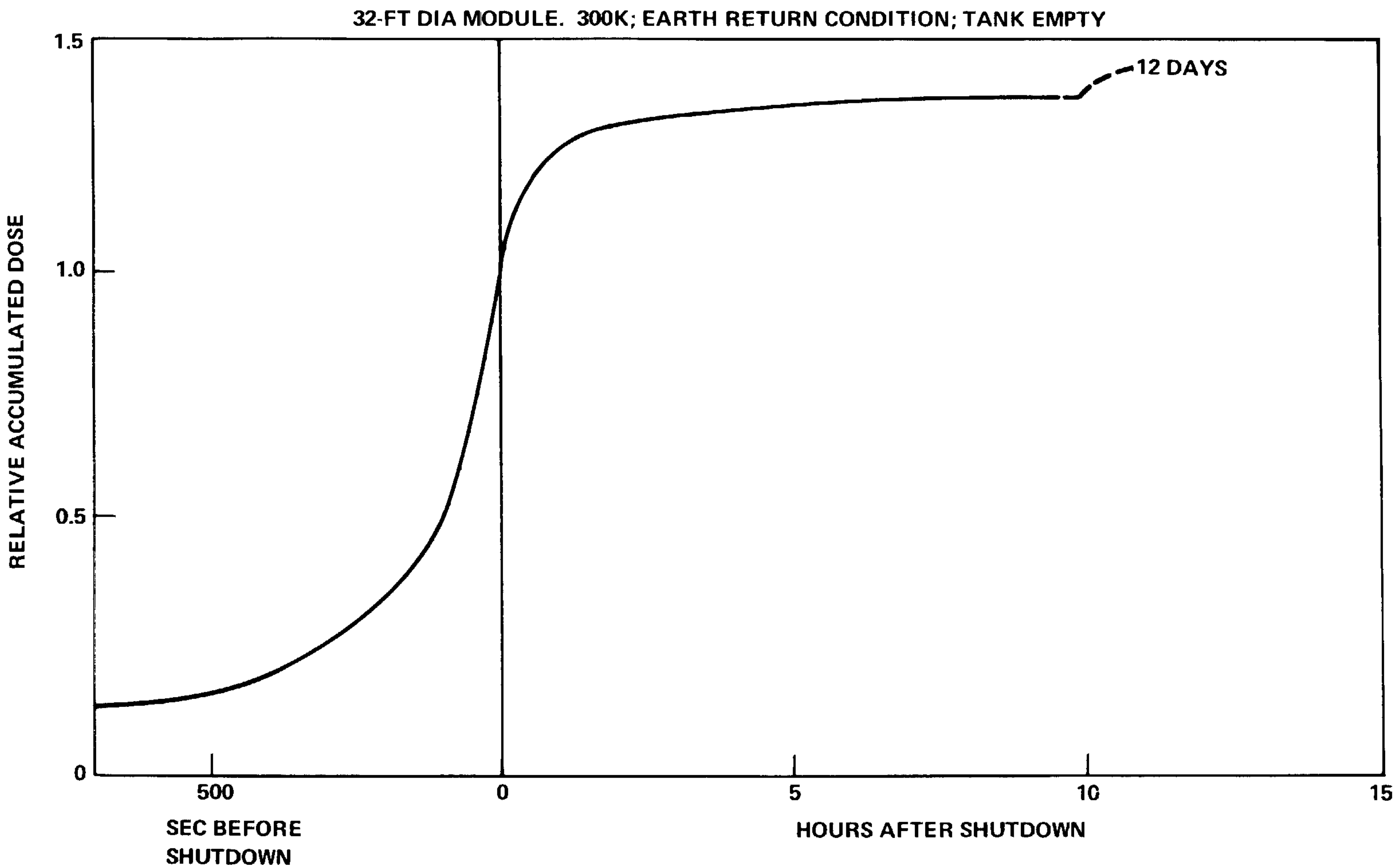


FIGURE 13 - TANK TOP ACCUMULATED DOSE

SOURCE – LMSC

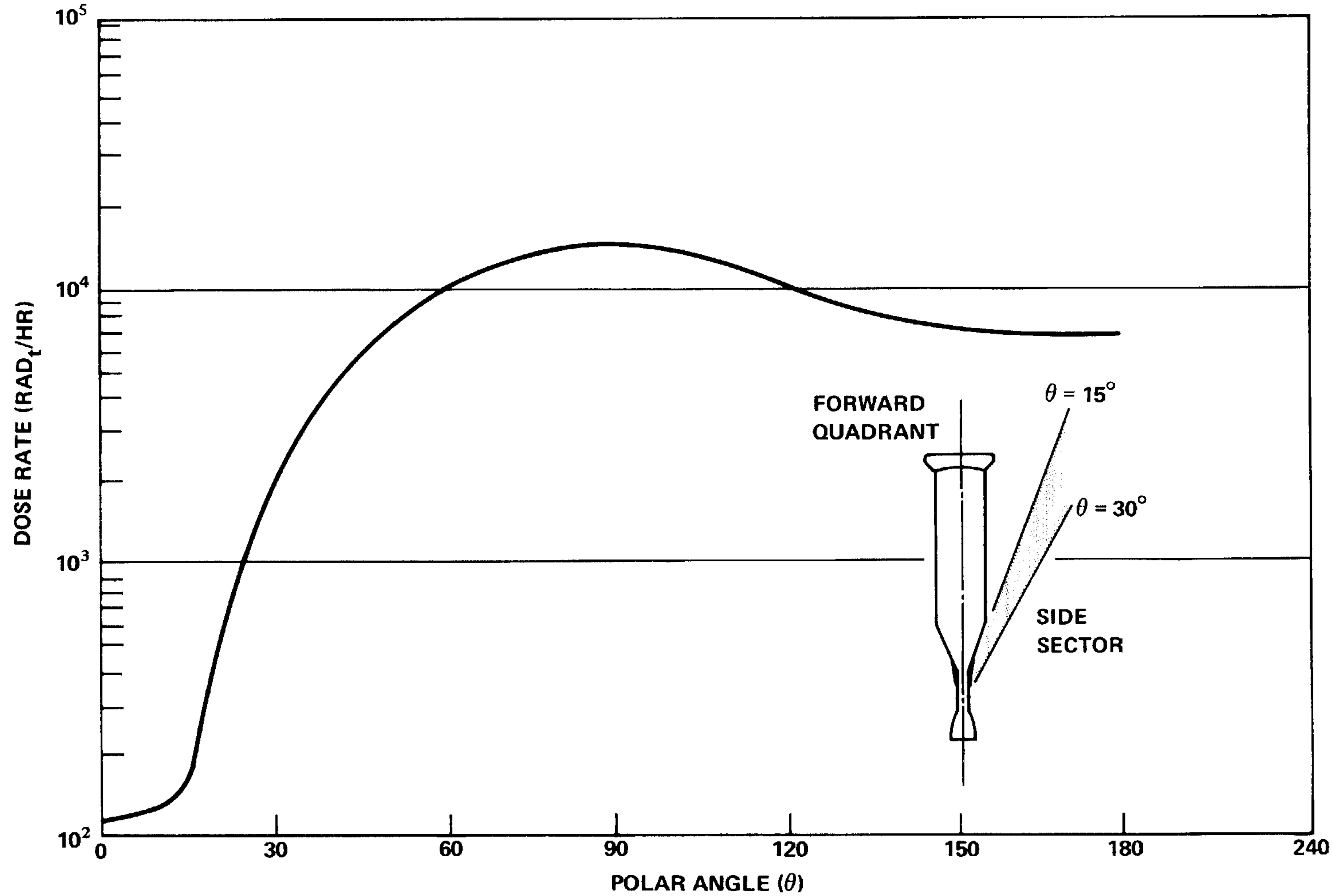


FIGURE 14 - DOSE RATE ON 100-FT MERIDIAN RING, 1000 SEC AFTER SHUTDOWN, SINGLE BURN, NO DISC SHIELD

SOURCE — LMSC

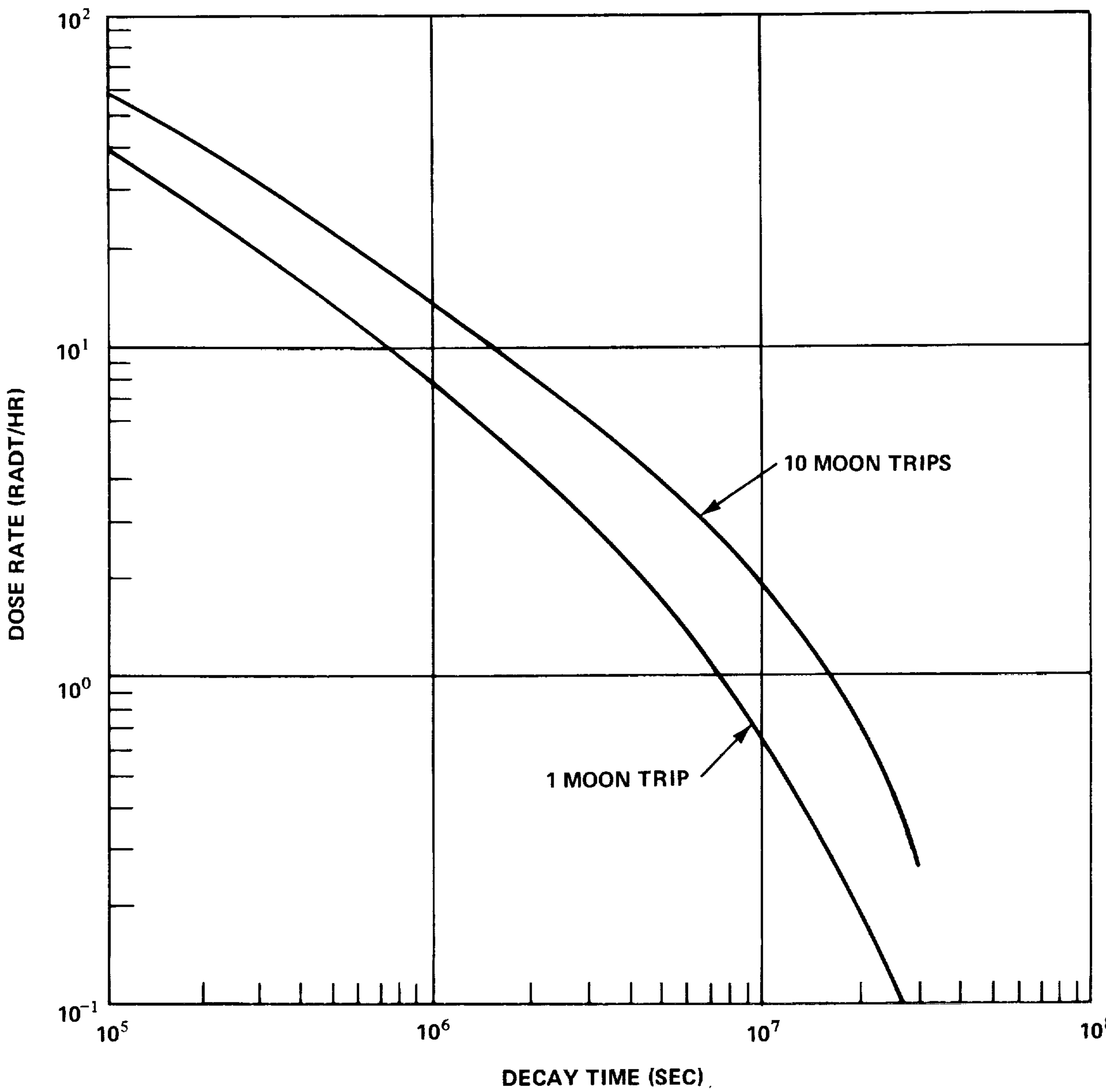


FIGURE 15 - DOSE RATE VS DECAY TIME, 100 FT FROM NERVA FISSION PRODUCT SOURCE, AT 90°

SOURCE – LMSC

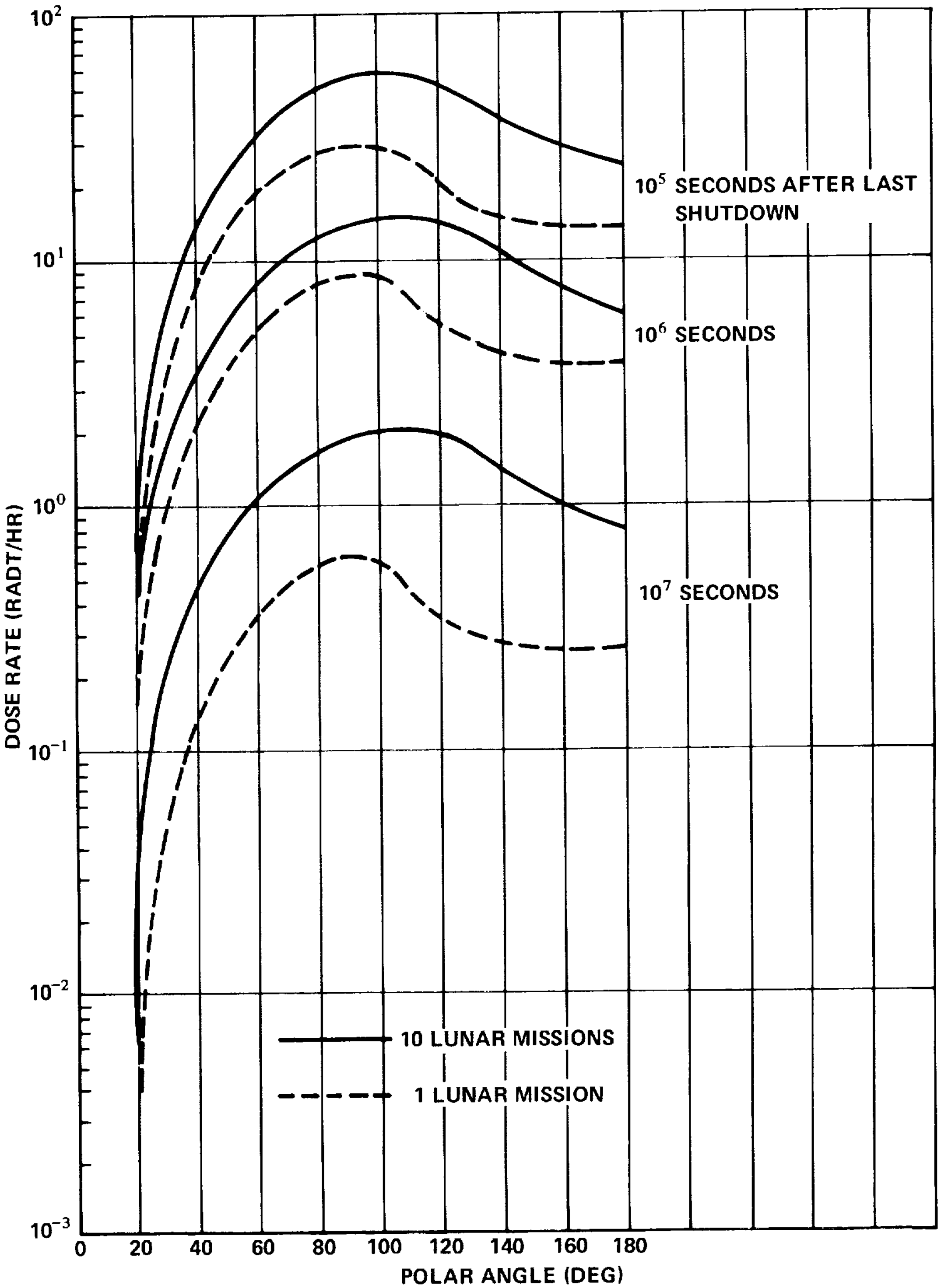


FIGURE 16 - DOSE RATE ON 100-FT MERIDIAN RING FOR A NERVA FISSION PRODUCT SOURCE

SOURCE – LMSC

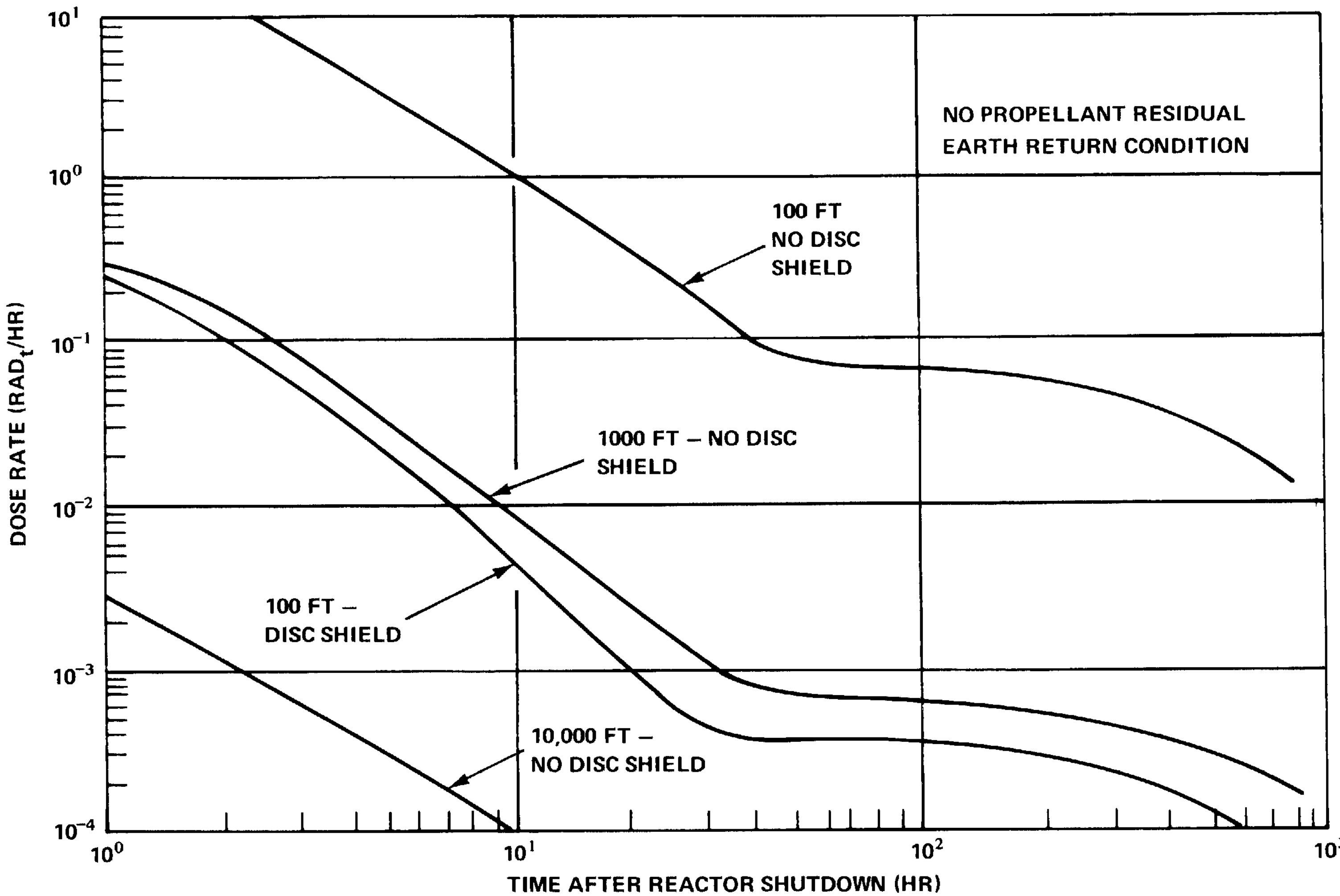


FIGURE 17 - FISSION PRODUCT DOSE RATES, FORWARD SECTOR, ONE TRIP

SOURCE – LMSC

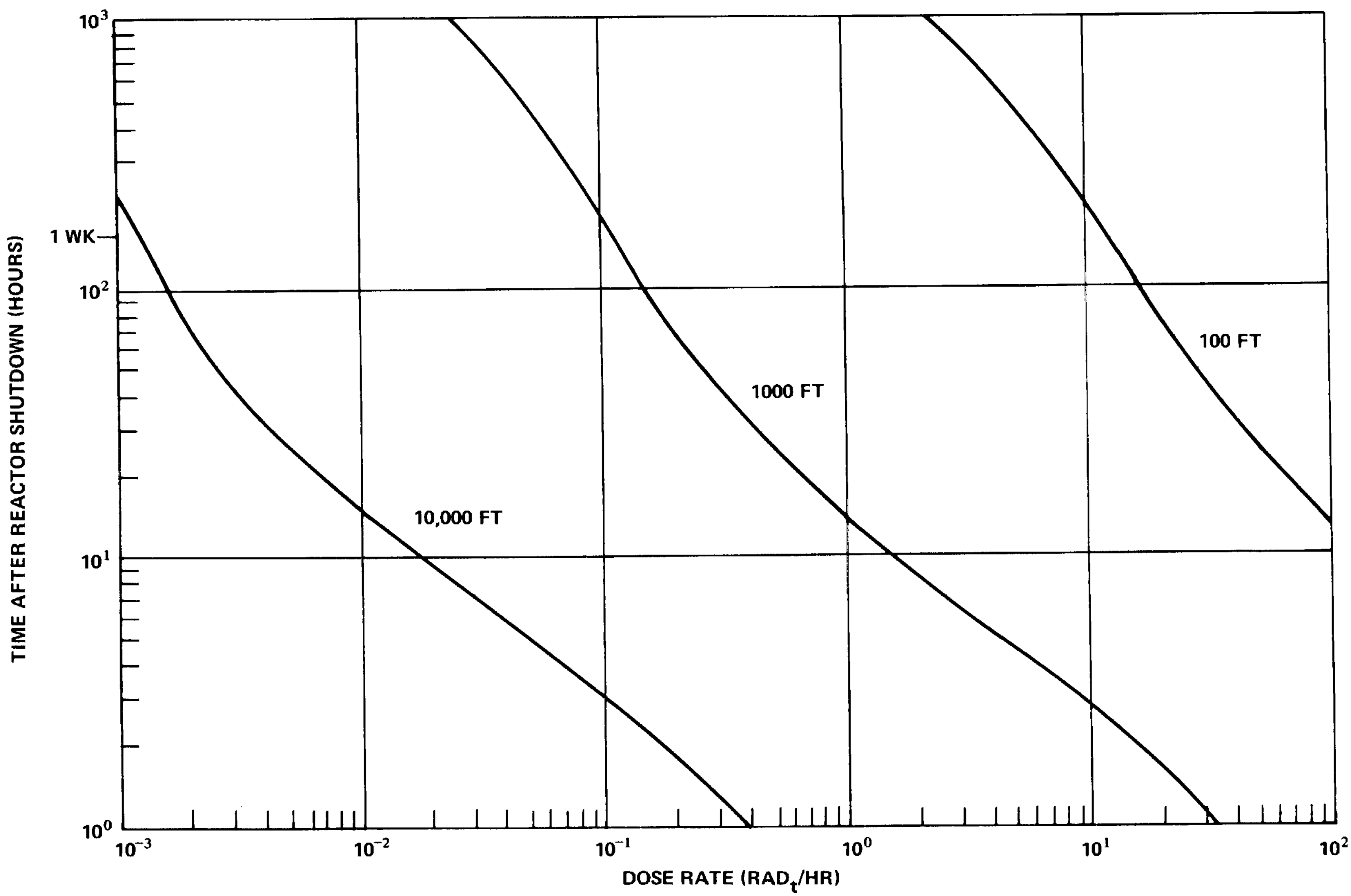


FIGURE 18 - FISSION PRODUCT DOSE RATES, SIDE SECTOR, EARTH RETURN CONFIGURATION, 1 LUNAR MISSION

SOURCE – LMSC

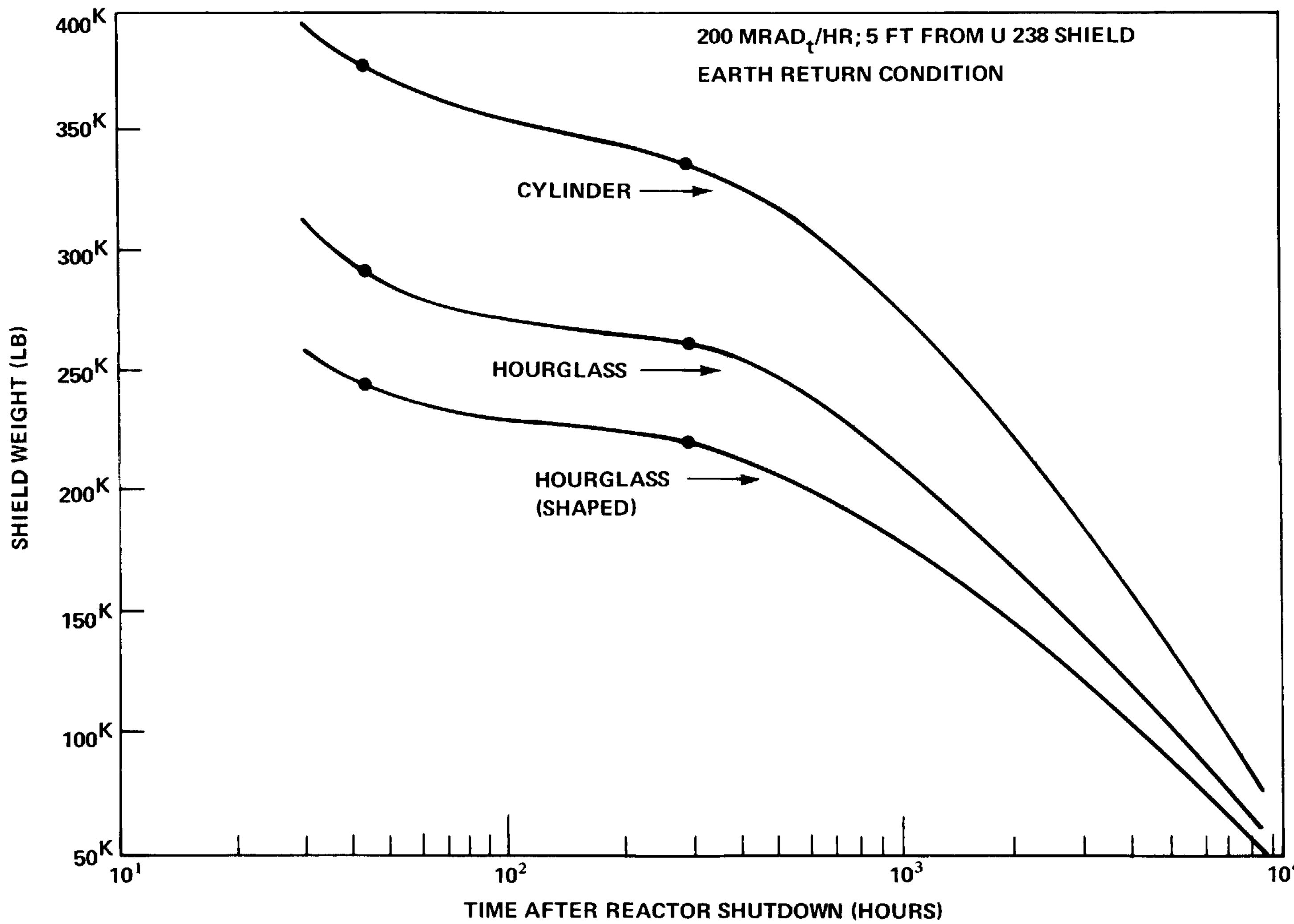


FIGURE 19 - ENGINE SPLIT SHIELD WEIGHT

SOURCE – LMSC

CALENDAR YEAR		80	81	82	83	84	85	86	87	88	89
LUNAR	LUNAR ORBIT STATION	6 MEN	6 MEN	6 MEN	6 MEN	6 MEN	12 MEN	12 MEN	12 MEN	12 MEN	12 MEN
		3	2	2	2	2	3	3	3	3	3
	LUNAR SURFACE BASE		6 MEN	6 MEN	12 MEN	12 MEN	18 MEN	24 MEN	24 MEN	24 MEN	24 MEN
			5	6	6	9	12	12	12	12	12
EARTH ORBITAL	GEOSYNCHRONOUS ORBIT STATION			6 MEN	6 MEN	6 MEN	6 MEN	12 MEN	12 MEN	12 MEN	12 MEN
				2	4	4	4	4	4	4	4
PLANETARY	UNMANNED PLANETARY	2	2	–	2	1	–	–	–	–	–
	MANNED PLANETARY									8	–
TOTAL RNS FLIGHTS (*)		5	9	10	14	16	19	19	19	27	19

FIGURE 20 - NUCLEAR SHUTTLE REFERENCE PROGRAM MISSION MODEL

SOURCE – MDAC

BELLCOMM, INC.

Subject: Status of Nuclear Flight System Definition Studies - Case 237

From: D. J. Osias

DISTRIBUTION

Complete Memorandum to

NASA Headquarters

W. O. Armstrong/MTX
P. E. Culbertson/MT
L. E. Day/MH
C. J. Donlan/MD-T
T. Hagler/MTE
E. W. Hall/MTG
T. A. Keegan/MTE
A. Liccardi/MF
D. R. Lord/MF
A. S. Lyman/MR
E. O. Pearson/RSD
A. D. Schnyer/MTE
W. A. Summerfelt/MH
A. O. Tischler/RS
W. W. Wilcox/RPT
J. W. Wild/MTE
W. H. Woodward/RP

AEC

P. G. Johnson/NPO
F. G. Schwenk/NPO

MSC

H. P. Davis/EA-4
J. Funk/JM8

MSFC

R. E. Austin/PD-SA-P
R. J. Harris/PD-SA-P
C. C. Priest/PD-SA-P
J. W. Russell/PD-SA-P
D. R. Saxton/PD-SA-P

Bellcomm, Inc.

G. M. Anderson
D. O. Baechler
A. P. Boysen
D. R. Hagner
E. E. Hillyard
P. F. Long
J. Z. Menard
J. M. Nervik
W. Strack
J. W. Timko
M. P. Wilson
All Members Depts. 1011, 1013
Central Files
Department 1024 File
Library

Abstract Only to

J. P. Downs
D. P. Ling
R. L. Wagner